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Auger Timing Effects on Performance of a Combine Unloading System

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Auger Timing Effects On Performance Of A Combine Unloading System

by

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Auger Timing Effects On Performance Of A Combine Unloading System

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Performance effects were measured on a combine unloading system using three different auger timing settings. Performance measures included maximum startup torque, mean operating torque, standard deviation of the operating torque, flow rate of grain through the system, and mechanical damage to the grain. The performance effects were measured with the system unloading corn and soybeans.

The data were statistically analyzed to check for interactions between the grains and differences between the timings. Using an alpha value of 0.1 it was found that timing 1 for both grains had a 3% (< 2.4 L/s) higher flow rate over timings 2 and 3. Timings 1 and 2 for both grains had higher maximum startup torque, about 10% (60 N·m) more torque required than timing 3. In soybeans, timings 2 and 3 also had the smallest standard deviation in operating torque, about 30% (20 N·m) less than timing 1. We were unable to detect any differences in mechanical damage to corn or soybeans as a result of unloading auger timing. These findings suggest that timing 3, with the cross augers lagging 90° behind the vertical unloading auger, may require less maximum startup torque and less variation in torque for the cross augers to effectively fill the loosely filled space left after the vertical auger lifts the grain without extra torque effects of having the augers push against each other as they do in timing 1.

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Introduction

Screw conveyors, more commonly referred to as augers, are the most common equipment used for moving grain and feed on farms. They have a low initial cost, low maintenance, simple construction and easy mobility. Many researchers have worked on experiments to determine the power requirements, mechanical damage to the grain, and flow rates with various designs of augers. Some of the factors in their research have included grain types, moisture contents, and method used to dry the grain. By far the biggest concern with augers is the mechanical damage inflicted to the grain. Damaged grain can ultimately result in spoilage leading to lower value of the grain. When augers are not operated at their optimum efficiency it typically results in lower flow rates, increased damage, excessive power usage, and excessive wear to the auger. Although much work has been done to analyze the damaging effect that a single auger has on corn and soybeans with varying speeds, capacity, and flighting design, very little has been done to determine what effects occur when a horizontal auger feeds a vertical auger.

Objectives

It was the overall objective of this study to determine the effects that relative auger positioning (auger timing) has on flow rate, mechanical damage and power requirements of the system moving corn and soybeans, when two equal size horizontal augers feed a single vertical auger. Setups like this are commonly found in modern combines to unload the clean grain tank.

Specific objectives were to determine:

1. For which of the three timings (relative position as specified by the combine manufacturer, 180° out of phase compared to the combine manufacturer's specifications, and 90° out of phase compared to the combine manufacturer's specification) was the grain flow rate the highest?
2. Which timing had the lowest maximum startup torque?
3. Did the average operating torque differ among the timings?
4. Which timing had the smallest standard deviation for the operating torque?
5. Was the interaction between grain types and timing significant for any of the performance parameters?
6. Did the timings have an effect on mechanical damage to corn or soybeans?

Review Of Literature

Auger Flighting Design

There are two basic types of auger flighting designs commonly used, single flighting and double flighting. With double flighting, at any point along the center axis of the auger there are two pieces of flighting attached to the center shaft, 180° apart from each other around the circumference of the center shaft. Double flighting should not be confused with short pitch flights. The pitch of the auger refers to the distance parallel to the center axis of the auger that the auger would move if it were screwed into a solid block as the auger rotated exactly one revolution. ASAE Standard EP 389.2 (ASAE, 2000a) states, "the most economical pitch on augers is equal to the flighting outside diameter. Pitches shorter than 0.9 O.D. and longer than 1.5 O.D. are generally not recommended." Reported in the Midwest Plan Service (1988) reports that "a pitch length equal to flight diameter (single pitch) gives the best performance under most conditions." Many researchers (Chang and Steele,1995; Hall,1974; Sands and Hall,1971) have done studies trying to determine which style of flighting is most suitable for all around use. It is widely accepted that while double flighting does have a higher conveying capacity and higher energy efficiency it does inflict a higher rate of mechanical damage when compared to conveyors with single flighting.

Chang and Steele (1995) studied auger performance with corn that had been dried with low temperature or high temperature air. They found that single-flight, standard pitch (pitch equal to flight diameter) augers caused the least amount of mechanical damage when compared with a double-flight, standard pitch auger and a single-flight, standard pitch auger with a strip welded to the outer edge of the flighting. Their results showed a significant increase in flow rate with the double-flight auger when compared to the single-flight auger.

Capacities and Power Requirements

Midwest Plan Service (1988) reports that auger capacity and horsepower are affected by diameter, pitch, speed (RPM), exposed intake length, incline, and grain properties. Overall length of the auger affects power requirement, but not capacity. As the speed of an auger increases the capacity and required horsepower to operate the auger will also increase. The increase in capacity and required horsepower is less for an auger that is inclined compared to a horizontal auger, or has a short intake opening to the auger. The capacity of an auger increases until the grain has difficulty entering the auger because the intake flighting throws it back out.

Hall (1974) showed the auger incline angle had a large effect on the rate of grain movement, but no significant effect on mechanical damage to soybeans. Midwest Plan Service (1988) indicates that for a given power, increased auger incline decreases capacity. As incline increases from horizontal , the power requirement increases to a maximum at inclines between 45° and 60°. At incline angles above 60°, capacity loss reduces the power requirement. At a 90° incline angle, the power required is about the same as for a horizontal auger, but the capacity is much less.

Midwest Plan Service (1988) also states grain type influences capacity and power requirements. An auger's capacity for wheat, grain sorghum, oats, barley, and rye is a little less than for corn. With soybeans, an auger has lower capacity and higher power requirements than with corn. Higher grain moisture content results in reduced capacity and increased power requirements because wet grain is heavier and has more friction. Grain depth over the auger intake, as in bulk tanks, increases auger horsepower needs, especially with long exposed intakes. Half pitch flights (pitch = ½ auger diameter) run at rated speed can reduce the amount of grain entering the auger and increase leverage, thereby reducing power requirements.

Corn Moisture Content and Kernel Damage

Several studies have been done to determine the effects that augers have on dried corn. Hall (1974) reported that even though wetter (>24%) corn is more elastic than drier corn, it is also more susceptible to damage due to the soft pliable wrinkles on the surface of the wet corn. Hall and Johnson (1970) found that the amount of corn/fine material that would pass through a 4.76 mm sieve decreased with decreasing moisture content to a minimum level at about 20 to 24 percent and then increased as the moisture content continued to decrease. Sands and Hall (1971) reported that a screw conveyor caused only a very small amount of damage to dry shelled corn when operated at full capacity. Al-Mosawi (1983) reported that in addition to economic losses, corn that is damaged at high moisture contents is susceptible to mold growth that can cause spoilage. This would seem to suggest that corn that is very low or high in moisture content will have an increased amount of damage when compared to corn in the 20 –24 percent moisture content range.

Corn Mechanical Damage Evaluation Test

The evaluation of mechanical damage to grain is one of the most vague problems associated with harvesting, handling, and marketing. Although many different methods have been used to evaluate mechanical damage, no consistent and conclusive method of damage evaluation is available. The Official Grain Standard of the U.S. Department of Agriculture (USDA, 1996) defined broken corn as the portion that readily passes through a 4.76 mm round hole sieve.

Chowdhury and Buchele (1975) developed a colorimetric test to determine bulk grain damage. Their test was based on the idea that the severity of damage would be proportional to the area of the exposed inner portion of the grain. They soaked their corn samples in a 0.1% solution of FCF Green Dye and the dye was absorbed by the exposed starchy area of the damaged grain. A solvent, 0.1% NaOH solution, was used to dissolve the absorbed dye from the damaged part of the grain. Then a simple colorimetric or an expensive spectrophotometer could be used to measure the amount of dye present in the solvent. The test was fast and accurate in describing the quality of the grain from the standpoint of mechanical damage.

Many researchers (Al-Mosawi, 1983; Chowdhury and Buchele, 1975; Pierce and Hanna, 1985; and Pierce et. al., 1991) have used the FCF Green Dye test as the method to evaluate corn for damage. Each has chosen to have slight variations in the process. The dye facilitates the identification of damaged kernels by absorbing to and coloring the damaged, exposed portion of the kernel. Pierce and Hanna (1985) submerged corn samples in a solution of 0.1% FCF Green dye, allowed the sample to soak in the solution for 5 minutes, rinsed with tap water, and then spread the kernels out on paper towels to air dry for 24 hours. Since each kernel must be examined separately, sample sizes must be small. The labor, time, and element of human fatigue may influence the results of a test such as this.

Soybean Moisture Content and Damage

Fernando (2001) reported that a substantial increase in mechanical damage occurred when soybeans below 11% to 12% moisture content were handled by threshing devices. Hall (1974) found that during handling, soybeans reached a minimum damage level at moisture contents of about 18% or 19%, while corn will have its minimum damage level at 24% to 25% moisture content.

He also noted that soybeans below 13% in moisture content were brittle and very susceptible to damage. This was especially the case when the auger was operated at less than full capacity and at a higher than normal speed.

Paulsen and Nave (1977) used a 0.1% indoxyl acetate-ethanol solution to identify soybeans with damaged seedcoats. They concluded that their test detected 84% to 100% of the soybeans known to have seed coat cracks. In addition, the test also found another 4% to 16% of the seed with minute seed coat damage that would have otherwise gone undetected by visual observation alone. In their study they compared their method to the sodium hypochlorite test and found very small differences in detection of damaged seed coats.

Fernando (2001) stated that rapid determination of soybean seed coat damage can be made with the sodium hypochlorite soak test. In his test, he immersed the soybean sample in a 0.1% sodium hypochlorite solution for 5 minutes, spread out the sample on paper towels, and recorded the soybeans that swelled to 2 to 3 times their normal size as damaged but unbroken. The sodium hypochlorite soak test is widely used by many researchers (Fernado, 2001; Paulsen and Nave, 1977; and Rodda et al., 1973) as the method to evaluate soybeans for mechanical damage.

Equipment and Procedure

A considerable amount of equipment was needed to carry out the experiment to evaluate the effects of unloading auger timing on system performance. This equipment included a torque transducer and calibration setup, a shaft speed sensor, a grain diverting system to determine the system flow rate, a computerized data acquisition and control system, and lab equipment to evaluate grain samples for mechanical damage. Most of this equipment was used in combination during each test run to obtain the necessary data. For ease of explanation each equipment set will be described separately.

Combine Harvester Specifications

A 2000 model year Caterpillar Lexion combine, model #460, serial # 9SW 553 was used for the entire unloading auger testing. At the end of the test the combine harvester's hour meter indicated it had been used for 759 hours on the unit, roughly 12 of those hours were put on the machine during these tests. The amount of time that the unloading augers had been used prior to our testing was unknown. The chopping unit attached to the rear of the combine harvester was engaged throughout the testing period.

The two cross augers in the bottom of the clean grain tank were identical with the exception that one had right-handed flighting and the other had left-handed flighting (Figure 1). The diameter of the cross augers was 190 mm (7.48 in) and the pitch was 180 mm (7.09 in). The overall length of these augers was 2349.5 mm (92.5 in). Of that length, 155 mm (6.11 in) was the length of the paddles at the discharge end of the horizontal cross augers.

The vertical unloading auger was equipped with double flighting on the first 250 mm (10.00 in) of the lower portion where grain is picked up from the two horizontal augers, with a flight-to-flight dimension of about 125 mm (5.00 in). Where there was not double flighting the flight-to-flight dimension (pitch) measured 225 mm (8.86 in). The diameter measured 340 mm (13.39 in) and the overall length of the auger was 1540 mm (60.63 in).

The diameter of the swing out auger was 300 mm (11.81 in), the pitch was 250 mm (9.84 in) and the overall length was 5532 mm (18 feet, 2 inches). The end of the swing out auger was equipped with a spout that would discharge the grain out and down from the end of the auger. Inside the grain tank, the tent covers over the unloading cross augers were positioned to allow the maximum amount of open inlet area on the inside of the two augers (side closest to the space between the two augers) and the covers on the outside of the augers were opened as far as possible throughout the testing period.

Unloading Auger Timing

The timing of the three unloading augers (rotational position relative to the other two) was the main independent variable in the experiment. Three levels of auger timing were used, including the correct timing (manufacturer's recommendation), 180° out of time, and 90° out of time. The drive sprockets for each auger had 40 teeth so the augers maintained the set timing as long as none of the sprockets jumped one (or more) teeth on the chain. Details of adjusting the auger to each timing level are as follows (see Figure 1):

Auger timing # 1: (Correct timing) Turn the vertical unloading auger so the leading edge (B) of the flighting that is continuous through out the length of the auger (the lower portion of the auger has double flighting) points towards the front of the combine harvester.

Turn the rear horizontal cross auger (4, feeding the grain from

	the bin to the vertical unloading auger) until leading edge (C) is pointing vertically to the top of the combine harvester. Turn the front horizontal cross auger (5) until the leading edge (A) is pointing vertically to the bottom of the combine harvester. Assemble the drive chain for these augers while maintaining these respective positions.
Auger timing # 2: (180° out of time)	Turn the vertical unloading auger so the leading edge (B) of the flighting that is continuous through out the length of the auger points towards the front of the combine harvester. Turn the rear horizontal cross auger (4) until the leading edge (C) is pointing vertically to the bottom of the combine harvester. Turn the front horizontal cross auger (5) until the leading edge (A) is pointing vertically to the top of the combine harvester. Assemble the drive chain for these augers while maintaining these respective positions.
Auger timing # 3: (horizontal cross augers lag 90° behind the vertical unloading auger)	Turn the vertical unloading auger to have the leading edge (B) of the flighting that is continuous through out the length of the auger pointing towards the front of the combine harvester. Turn the rear horizontal cross auger (4) until the leading edge (C) is pointing horizontally towards the front of the combine harvester. Turn the front horizontal cross auger (5) until the

leading edge (A) is pointing horizontally towards the front of the combine harvester. Assemble the drive chain for these augers while maintaining these respective positions.

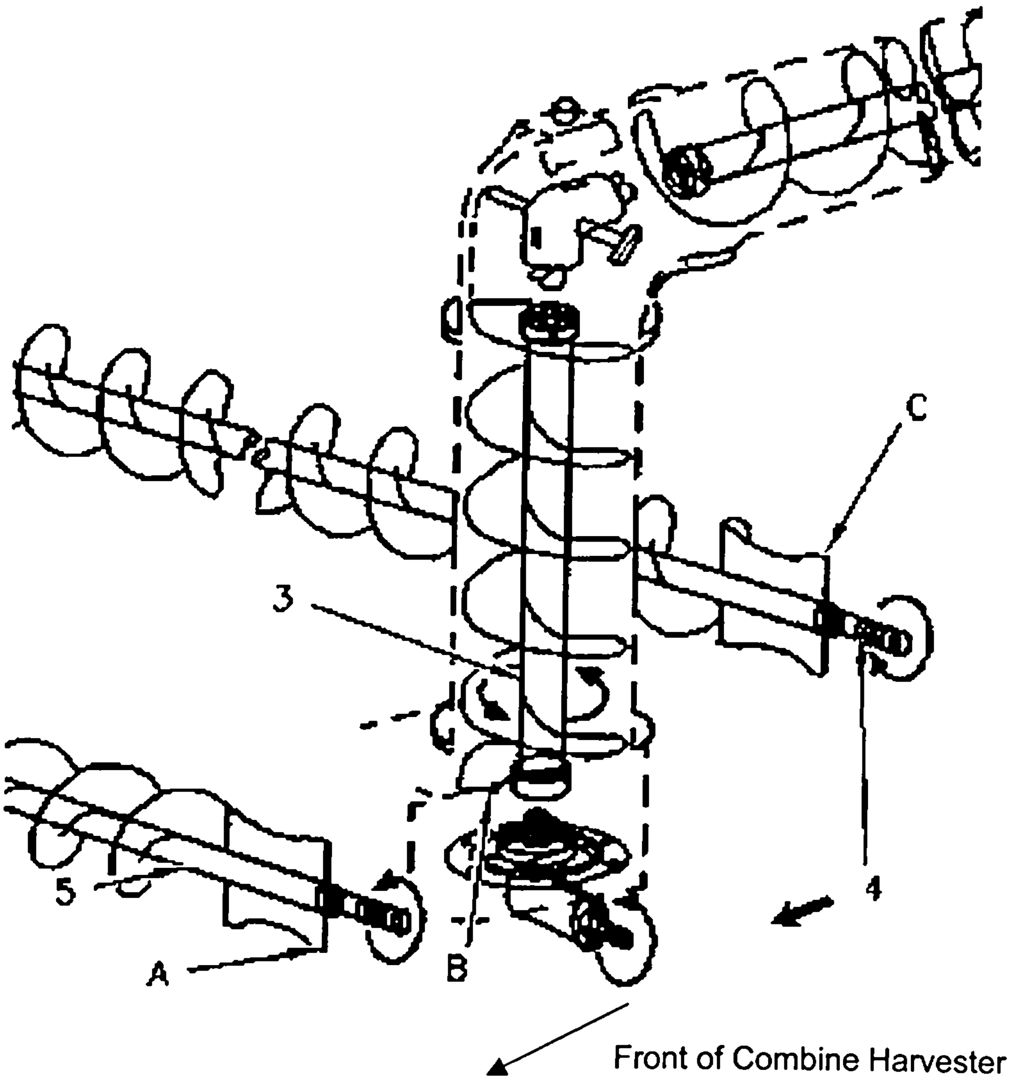

Figure 1. Schematic drawing of the front (5) and rear (4) horizontal cross augers and the vertical (3) unloading auger set at the manufacturer's recommended timing. Source: Used with permission from Lexion (Caterpillar,1998) Combine Operator's Manual.

Unloading Auger System Drive Shaft Torque

The horizontal cross augers and the vertical unloading auger were all driven from a single shaft (Figure 2). The sprocket for the chain drive of the unloading augers was on one end of this drive shaft and a v-belt sheave on the opposite end supplied input power to the unloading auger drive system. Start up and operating torque were monitored through the use of full bridge torque transducer constructed on the middle of this drive shaft using torque strain gages (Micro Measurement CEA-06-187UV-350, Measurements Group, Inc., Raleigh, NC). A slip ring (S4, Michigan Scientific Corp., Milford, MI) was attached to the v-belt sheave end of the shaft, for conducting supply voltage to the torque transducer, and conducting the output signal to the data acquisition and control computer.

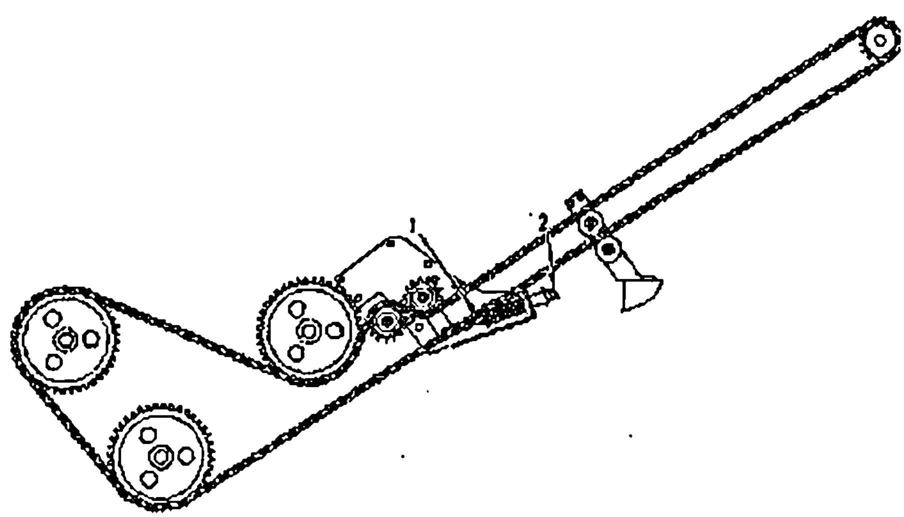

Figure 2. Schematic drawing of the chain drive for the auger system. Source: Used with permission from Lexion (Caterpillar,1998) Combine Operators Manual.

The data acquisition computer was used to supply a regulated excitation voltage of 5VDC to the torque transducer. The torque cell output voltage was amplified with an instrumentation amplifier (Analog Devices AD624, One

Technology Way. Norwood, MA) configured with a nominal gain of 375. The output from the amplifier was connected to one of the 12 bit analog-to-digital converter channels on the data acquisition computer. A calibration jig was built to hold the shaft stationary while known torques were applied to the shaft with weights hung from a lever arm. The calibration was done with the slip ring and all the lead wires that would be used once the torque cell was in place in the combine harvester and the data acquisition computer to account for all system components in the calibration. The calibration and verification data for the torque transducer are shown in Figure 3. The R^2 for the calibration equation was 0.997 and the maximum error in the verification data was 4.44 N•m, indicating a 3.36 percent resolution.

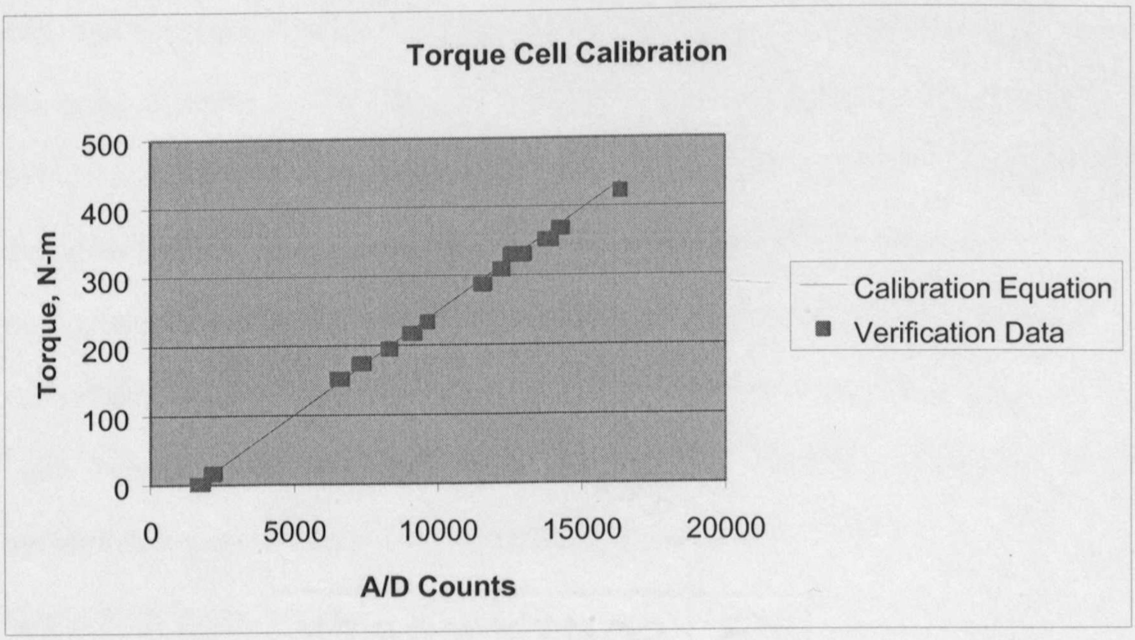

Figure 3. Graph showing calibration and verification data from calibrating the torque cell on the unloading auger drive shaft.

Rotational Speed of Unloading Auger System Drive Shaft

The rotational speed of the drive shaft for the unloading auger system was obtained using an inductive proximity sensor (NJ5-18GM50-E0. Pepperl+Fuchs Inc. Twinsburg, OH). The sensor was set up so each time a tooth of the unloading system drive sprocket passed in front of the sensor it sent a 5VDC square wave pulse to the data acquisition computer. The data acquisition computer monitored the period of these pulses and was programmed to record the rotational speed of the drive shaft in revolutions per minute.

Data Acquisition Computer

A single board data acquisition and control computer (TFX-11, Onset Computer Corporation. Bourne, MA.) was used to collect data from the torque cell, and shaft speed sensor, and to operate a directional control valve controlling the grain diverting system. A toggle switch was used to signal the computer when to start collecting data. After each test run, the data collected by the computer was downloaded to a laptop computer. The single-board data acquisition computer was housed in a standard 5 gallon plastic bucket with a tight-fitting rubber-gasketed lid for portability and protection from the elements during the tests. The computer program used to obtain data and control the grain diverter system during each test run is presented in Appendix A.

Grain Flow Rate

The mass flow rate of grain out of the unloading system was measured following ISO Standard 5687:1999 (ISO, 1999). For this experiment, corn (#2 yellow corn) and soybeans (#1 yellow soybeans) were used instead of wheat as described in the Standard. Before each test run about 100 bushels of the test grain was moved from storage through an inclined auger (separate from the combine harvester) and dumped into the clean grain tank of the combine from above.

At the start of each test run the unloading augers were operated for about six seconds after they first started rotating to allow time for full steady flow to develop. During this startup time, the grain diverting system directed the discharge from the combine harvester unloading auger into the grain truck. At the end of the six second startup time the diverting system was triggered by the data acquisition computer to direct the discharge from the combine harvester into the weigh wagon (Brent, 470, Kalida, OH). Grain was discharged into the weigh wagon for about 25 seconds and then the data acquisition computer triggered the grain diverting system to direct the discharge back into the truck until the combine harvester was empty. At the end of the test, the weight of the grain in the weigh wagon was recorded.

Two separate samples of the grain were collected from the stream of grain as the separate auger was used to move grain into the combine harvester grain tank. A 19 L (5 gal) bucket was used to collect the grain sample which was used to determine the grain test weight and moisture content. A 76mm (3 in) diameter PVC pipe with a 25 x 130mm (1 x 5 in) slot cut into the side of one end of the pipe was used to collect the grain samples used to determine the level of damage in the grain before each test run. The PVC pipe sampling device was also used to obtain samples from the grain stream discharge from the combine unloading system to determine the level of damage in the grain after each test run. The openings of both collection devices were passed through the grain stream at least 3 times to get a representative sample of the grain. This procedure was used for both soybeans and corn.

Calculation of Flow Rate

A grain diverter system was built to divert the discharge from the combine harvester unloading auger into either a grain truck or a weigh wagon (Figure 4 and 5). The diverter measured approximately 0.91 m by 0.91 m (3.0 ft by 3.0 ft) and 0.61 m (2.0 ft) tall with a plate (butterfly) that pivoted on a horizontal shaft in the center to direct the flow. The butterfly plate was actuated with a 26.9 mm (1.06 in) bore by 203.2 mm (8.00 in) stroke pneumatic cylinder (Select, SLD11-CBP-080, Indianapolis, IN). The pneumatic cylinder was operated by a 12 Volt DC, 2 position, 5 way, solenoid operated, spring return directional control valve (NVS 4114-25510TN, SMC Pneumatic Inc. Indianapolis, IN), controlled by the data acquisition computer. The on/off operating pressures for the compressor that provided the air to operate the cylinder were set at about 620 and 960 kPa (90 and 140 psi). The time that actual flow was diverted into the weigh wagon was monitored by the use of two Hall-Effect switches (SS41/SS41D Honeywell Inc. Freeport, IL) triggered by magnets (PK 8909 3 Honeywell Inc. Freeport, IL) attached to the bottom side of the butterfly plate (Figure 6). A digital storage oscilloscope (Nicolet Pro, Madison,WI) was used to record the output voltage from each channel of the Hall-Effect switches with time.

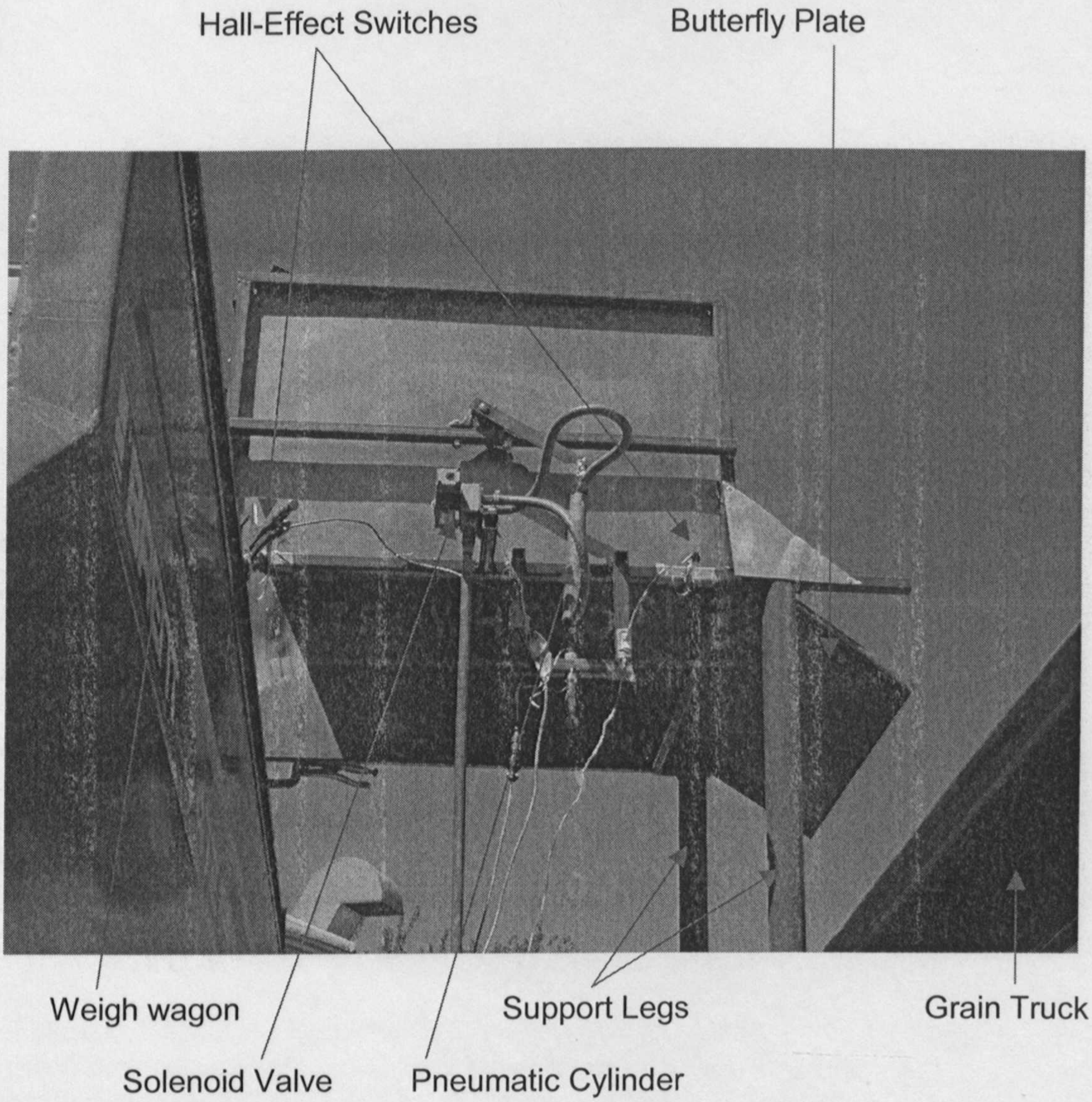

Figure 4. Grain diverter system used to divert the discharge from the combine harvester unloading auger into either the grain truck or the weigh wagon. Note that the butterfly plate as shown is set to divert the discharge (which falls on top of the butterfly plate) into the grain truck.

Figure 5. Combine harvester discharging corn out the unloading auger into the grain diverting system. In this picture the grain diverting system is directing the grain flow into the grain truck.

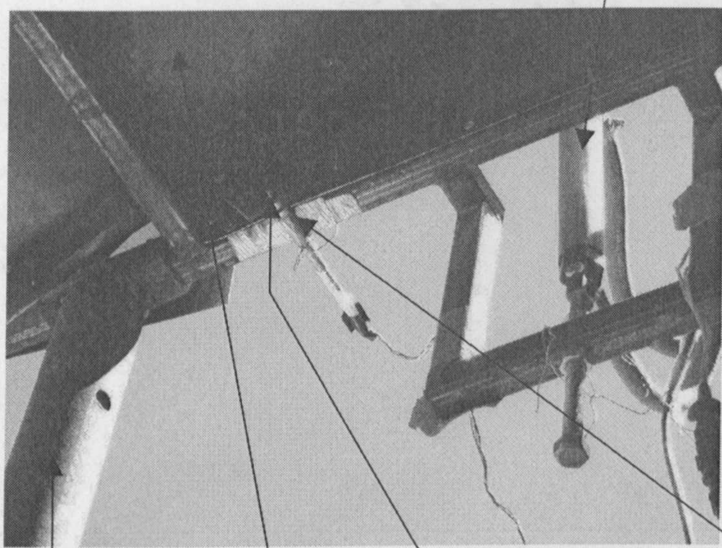

Figure 6. View from underneath the grain diverting system, looking up at the butterfly plate, magnet and Hall-Effect sensor.

During a complete cycle, three time measurements were recorded to determine the time during which the grain discharge from the combine unloading auger was directed into the weigh wagon. At the start of each test run the butterfly plate of the grain diverting system was set to direct the flow into the grain truck. With the butterfly plate in this position, both Hall-Effect sensors (channel 1 on the grain truck side and channel 2 on the weigh wagon side) were set to output a high voltage (5VDC) (Figure 7). After steady flow developed, the data acquisition computer triggered the solenoid valve to move the butterfly plate so grain flow was directed into the weigh wagon instead of the grain truck. As the butterfly plate began to move, the magnet on the grain truck side of the butterfly plate moved out of range of the Hall-Effect sensor channel 1 (grain truck side) and the voltage on this channel dropped to almost 0VDC. Thus the first voltage change on channel 1, from 5V to 0V signaled the start of the movement of the butterfly plate to switch the grain flow into the weight wagon. As the butterfly plate completed its movement to switch the grain flow into the weigh wagon, the magnet on the weigh wagon side of the butterfly plate came into range of the Hall-Effect sensor on that side and the voltage (channel 2) dropped from 5V to near 0V.

At the end of the time period during which the grain discharge from the combine unloading auger was collected in the weigh wagon, the computer triggered the solenoid valve to move the butterfly plate so the discharge was directed into the grain truck instead of the weigh wagon. As the butterfly plate began this movement, the voltage on channel 2 (weigh wagon side) increased from 0V to 5V. As the butterfly plate completed this movement, the voltage on channel 1 (grain truck side) increased from 0V to 5V. These two voltage-time traces were recorded on the oscilloscope and the following three time intervals were measured from these data to determine the time interval during which the grain discharge from the combine unloading auger was collected in the weigh wagon.

t_1 — time from start of voltage drop on channel 1 to end of voltage drop on channel 2

t_2 — time from start of voltage drop on channel 1 to start of voltage increase on channel 2

t_3 — time from start of voltage drop on channel 1 to end of voltage increase on channel 1

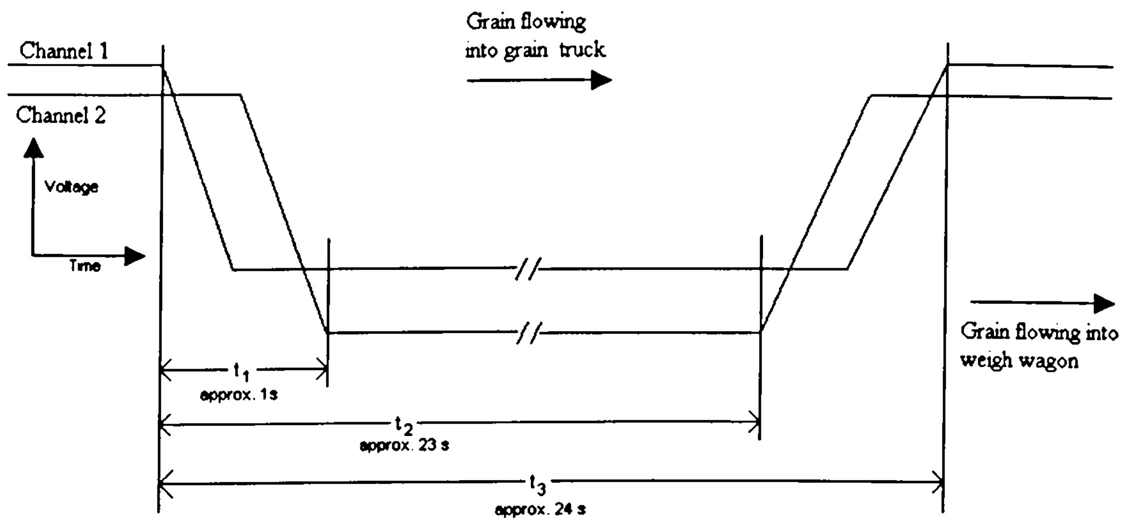

Figure 7. Hall-Effect sensor voltage-time traces recorded on the oscilloscope for determination of the time interval during which the grain discharged from the combine unloading auger was collected in the weigh wagon.

Using these time measurements, the time interval during which the grain discharge from the combine unloading auger was collected in the weigh wagon was estimated as the total time, t_3, minus one-half the time it took for each of the two butterfly plate movements, t_1 and $t_3 - t_2$. Thus flow time was then calculated by equation 1:

$$Flow\,time = t_3 - \frac{(t_3 - t_2)}{2} - \frac{t_1}{2} \qquad [1]$$

The test weight of the grain for each test run was measured at the end of each days' testing using a test weight device (Test Weight Device Seedburo Equipment Co., Chicago, IL) using the sample taken with the 5 gallon bucket from the grain stream as the combine harvester was being loaded with the test grain. This measurement was necessary to convert the weight measurement of grain in the weigh wagon to number of bushels. A mean flow rate of the unloading auger could then be calculated using equation 2.

$$F = \frac{W_W}{T_W \cdot t} \quad [2]$$

where:

F is the mean flow rate, liters per second (bu/s)

W_w is the mass (weight) of the grain collected in the weigh wagon, kg (lb)

T_w is the test weight of the grain, kg/L (lb/bu)

t is the time interval during which the discharge from the combine harvester unloading auger was directed into the weigh wagon, s.

The same sample of grain that was used for measurement of test weight was also used for measurement of moisture content, at the end of each days' testing. Moisture content was determined using a moisture meter (Model #SS250, Steinlite Moisturemeter, Fred Stein Laboratories, Inc. Atchison, KS).

Operational Procedures

The tests were performed from August 12 to August 22, 2002 at the Biological Systems Engineering Department Rogers Memorial Farm approximately 10 miles east of Lincoln, Nebraska. Four replications of each of the three timing treatment levels were done to provide necessary data for statistical analysis. The order in which the timing treatments were applied was randomized (Appendix B).

After all equipment was readied and people were in place, the following steps were used to begin a test run:

1. Engage the threshing unit with the combine harvester's engine at idle.
2. Throttle engine up to rated speed.
3. Switch header to operating position.

The machine was now ready to make a test run. The following series of events occurred to gather the required data.

1. The start switch for the data acquisition computer and start switch for the unloading auger system were triggered simultaneously.
2. The computer waited for 4.5 seconds to account for the unloading auger system startup delay.
3. The computer then recorded 200 torque values at 0.01 second intervals, to obtain peak start-up torque.
4. The torque readings were immediately followed by recording the rotational speed of the unloading auger system drive shaft.
5. The computer waited 6 seconds to allow time for full steady flow to develop.
6. The solenoid was activated to extend the pneumatic cylinder to move the butterfly plate of the grain diverting system so grain flow was directed into the weigh wagon instead of the grain truck.

7. 11.5 seconds after flow was directed into the weigh wagon 100 torque values were recorded at 0.01 second intervals to obtain operating torque requirements.
8. The torque readings were immediately followed by measuring (about 1s) and recording the operating rotational speed of the unloading auger system drive shaft.
9. 11.5 seconds after the operating speed was taken the solenoid was deactivated (cylinder retracted) so grain flow was directed into the grain truck instead of the weigh wagon, until the combine harvester's grain tank was empty.

Sampling Procedure for Grain Quality

Samples of the grain were taken before and after each test run so these samples could be evaluated for grain quality. The change in grain quality was attributed to the treatment. It was estimated that the grain had already been through as many as seven different augers by the time it was loaded into the combine harvester grain tank. The pre-treatment sample was collected across the full width of the flow stream of the grain as it left the auger used to fill the combine harvester grain tank. The post-treatment sample was collected from across the full width of the flow stream of the grain as it left the discharge end of the combine harvester unloading auger, after the timed collection of grain flow in the weigh wagon.

Both the pre- and post-treatment samples obtained with the collection device were randomly divided into two 100 g samples. The samples were double bagged in plastic zippered freezer bags and then stored in a refrigerator at 5°C until the time of damage evaluation.

Evaluation of Mechanical Damage to Corn

To prepare the pre- and post-treatment samples for quality evaluation, each sample was spread out onto a tray where dockage was removed (other grains, insects, pieces of plant material, etc). The dockage free sample was then weighed and the sample weight was recorded. Next the broken corn (BC) was screened out with at least 20 strokes of a standard dockage sieve for corn (4.76 mm diameter round hole). Material that passed through the sieve was weighed and recorded as BC.

Kernel damage was evaluated by treating the corn remaining on top of the dockage sieve with 0.1% Fast Green Dye solution to facilitate the identification of damaged kernels. Samples were immersed for 5 minutes in the solution, thoroughly rinsed in running water, then spread on a paper towel for a few hours to air dry before being analyzed. After drying, the samples were visually inspected and divided between no damage, minor damage and severe damage. Samples were classified into the following categories (Figure 8) according to the severity of damage:

1. Severe damage — Broken pieces, large pericarp (hull) cracks or missing endosperm
2. Minor damage — Absorbed FCF or pericarp (hull) cracks
3. No damage — Slight amount of FCF on tip cap

The damage categories were reported as a percentage of the sample weight after the dockage had been removed. Since the minor and severe damage portions had been exposed to moisture in the dying process the weight of these portions of the sample had changed. Thus, these portions weights needed to be recorded with some way of representing their weight prior to being immersed in the green dye solution. Therefore, the damaged portions were dried at 105°C for 72 hours to get dry weights, and then Equation 3 (ASAE, 200b) was used to convert the dry weights of these portions to wet basis weights at the moisture content originally record for the sample:

$$G_w = \frac{100\,G_d}{100 - MC_{wb}} \qquad [3]$$

where:

G_w is the mass of wet material

G_d is the mass of dry material

MC_{wb} is the wet basis moisture content of sample at time of collection

Evaluation of Mechanical Damage to Soybeans

To prepare the pre- and post-treatment samples for quality evaluation, each sample was spread out onto a tray where dockage was removed (other grains, insects, plant material, etc). The sample was sieved with at least 20 strokes through a 4.00 mm round hole sieve. Material that passed through the sieve was recorded as "splits". The splits were weighed to get a percent (by weight). No splits were recorded throughout all the samples. The fraction of mechanically damaged but unbroken seeds was determined by the sodium hypochlorite test. Two replicates of one hundred soybeans were randomly selected from each sample and immersed in a 0.1% sodium hypochlorite solution for 5 minutes. The sample was spread out onto paper towels (Figure 9) and the enlarged soybeans were counted and recorded as a percent (by number).

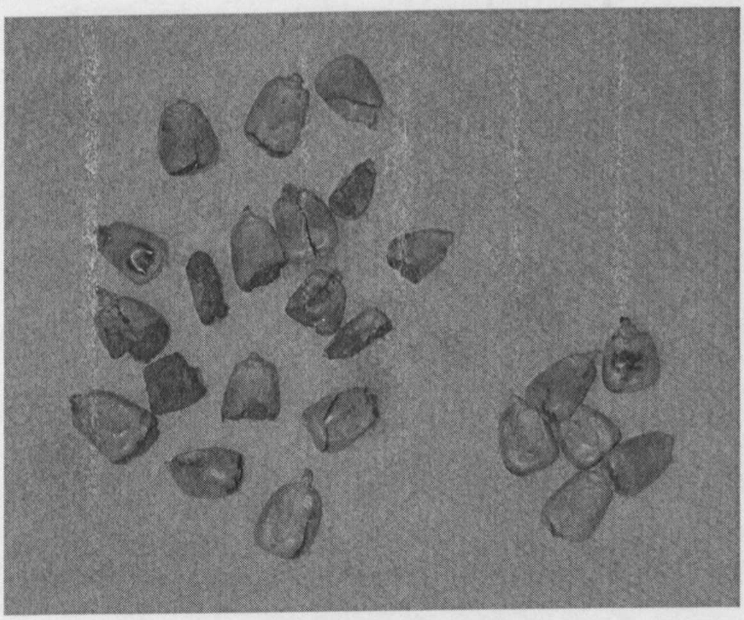

Figure 8. Corn mechanical damage evaluation after being soaked in 0.1% FCF Green Dye for 5 minutes. Kernels on the right were classified as minor damage. Kernels on the left were classified as severe damage.

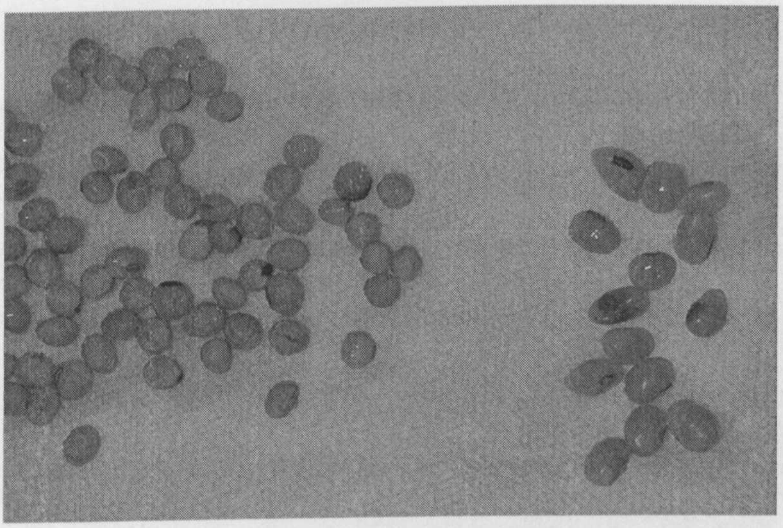

Figure 9. Soybean mechanical damage evaluation after being soaked in 0.1% sodium hypochlorite for 5 minutes. Soybeans that were classified as unbroken but damaged are on the right side of the figure. Soybeans on the left were classified as undamaged.

Data Analysis

The data analysis was done in two steps. The data recorded by the data acquisition computer were first analyzed with a Q-Basic (Quick Basic 4.50 1985-1988 Microsoft Corp, Redmond, WA) program to filter out poor torque data points (maximum or minimum torque values for the transducer, indicating poor electrical connection at the slip ring) and calculate maximum startup torque, average operating torque, standard deviation of the operating torque, and number of good operating torque values. Each of these torque values was important to illustrate what effects and requirements auger timing had on the unloading system. The results from the Q-Basic analyses were then entered into Excel (Microsoft Excel 2000, v9.0.4402 SR-1 Microsoft Corp, Redmond, WA) along with the flow rate, mechanical damage, and moisture content for each grain. Figure 10 is a sample graph of startup torque data, Figure 11 shows a sample graph of operating torque data, and Figure 12 is a sample graph of operating torque data with a few data points pegged high and low that the Q-Basic program would remove from the analysis.

All the data were entered into SAS (SAS Institute,Inc.,2000) and an analysis of variance was carried out using PROC MIXED to determine if there were significant differences in auger timings. The design was a 3 x 2 factorial (3 levels of auger timing and 2 grain types) and the interaction between grain and timing was investigated. However, the mechanical damage evaluation technique was different for corn and soybeans so they could not be checked for interactions. Thus, two separate analyses were run for the grain to determine significant differences in grain quality among auger timings.

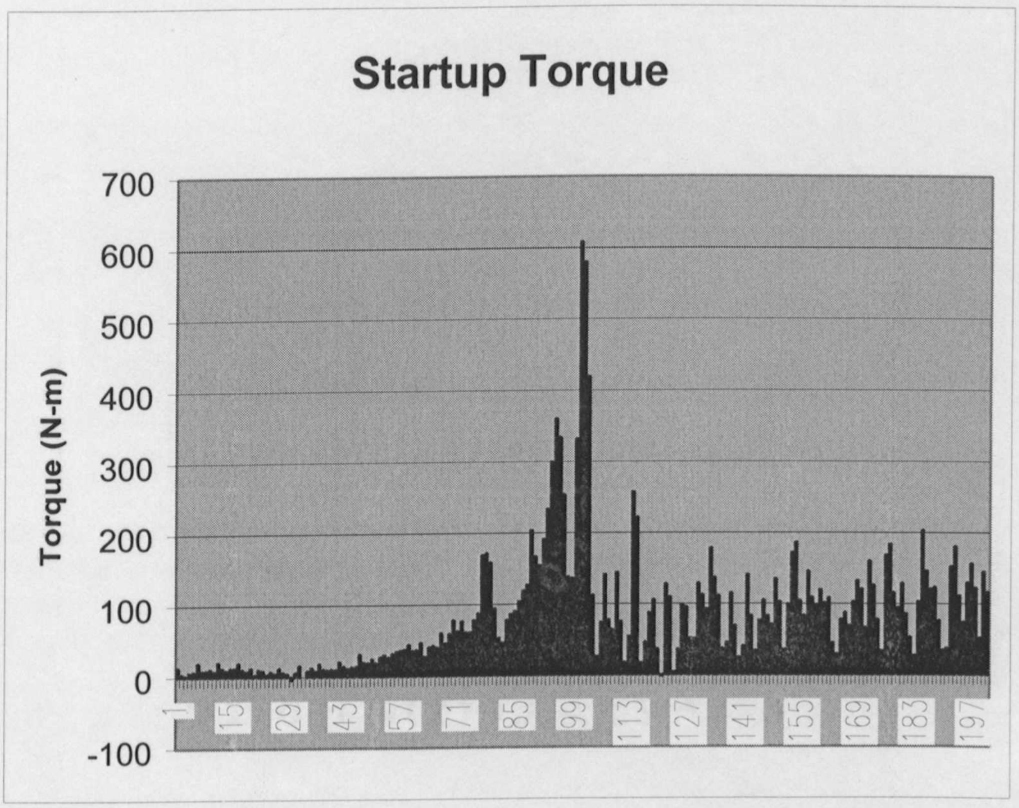

Figure 10. An example graph constructed from 2 seconds of startup torque data, sampled at a rate of 100 times per second when unloading augers were engaged. Data from the test run rep 1, using corn, and auger timing 3 (1C3).

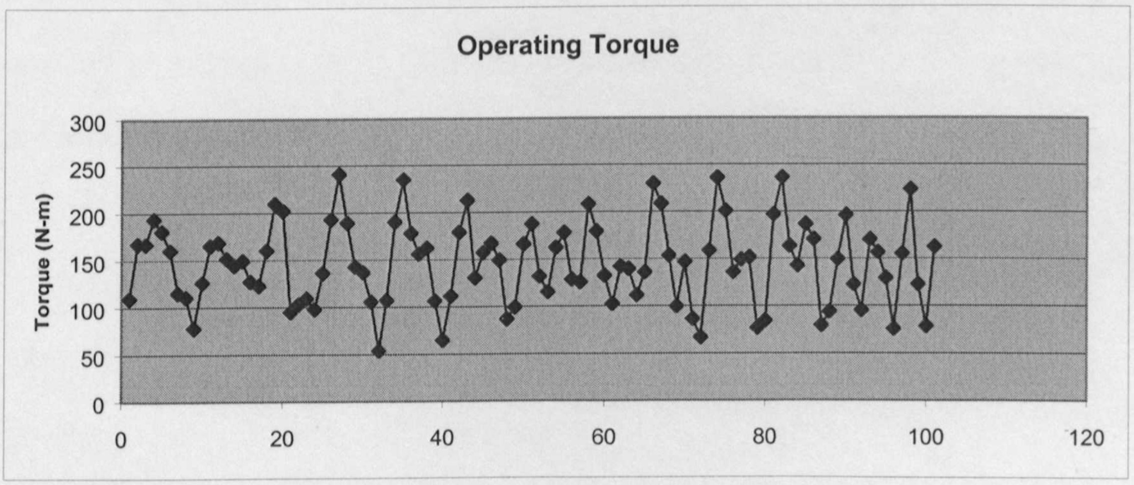

Figure 11. An example graph constructed from 1 second of torque data sampled at a rate of 100 times per second when the unloading augers were operating at a steady state. Data from test run rep 1, using soybeans, and auger timing 2.

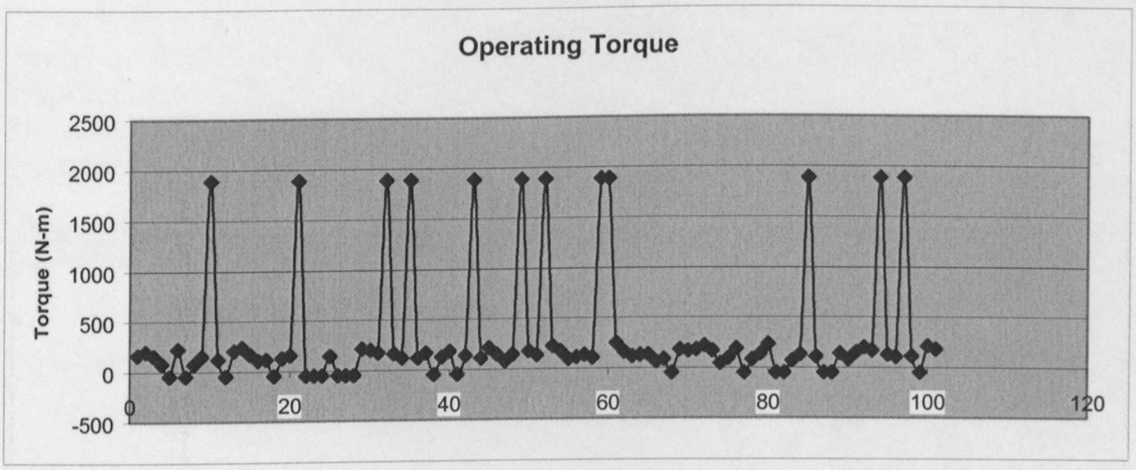

Figure 12. An example of 1 second of running torque with a few data points erroneously at maximum or minimum torque values for the transducer. The maximum and minimum torque values were not used in the analysis. Data from rep 4, with corn, and auger at timing 1.

Results And Discussion

Table 1 shows the values for flow rate, maximum startup torque, average operating torque, standard deviation of operating torque and moisture content, averaged over four replications for each timing treatment with corn. Table 2 shows the values for the same list of response variables averaged over the four replications for each timing treatment with soybeans. Data from each replication are shown in Appendix C-1.

Table 1. Flow rate, maximum startup torque, average operating torque, standard deviation of operating torque, and sample moisture content averaged over the four replications for each combine harvester unloading auger system timing treatment with corn. The standard error for each measurement is shown in parenthesis after the measured value.

Corn					
Timing	Flow Rate (L/s)	Max. Startup Torque (N·m)	Average Operating Torque (N·m)	Standard Deviation of Operating Torque (N·m)	Moisture Content (%)
1	89.15 (0.493)	645 (16.72)	145 (4.46)	45 (5.49)	12.6 (0.172)
2	86.69 (0.493)	610 (16.72)	145 (4.46)	45 (5.49)	12.2 (0.172)
3	87.04 (0.493)	580 (16.72)	155 (4.46)	50 (5.49)	12.7 (0.172)

Table 2. Flow rate, maximum startup torque, average operating torque, standard deviation of operating torque, and sample moisture content averaged over the four replications for each combine harvester unloading auger system timing treatment with soybeans. The standard error for each measurement is shown in parenthesis after the measured value.

Soybeans					
Timing	Flow Rate (L/s)	Max. Startup Torque (N·m)	Average Operating Torque (N·m)	Standard Deviation of Operating Torque (N·m)	Moisture Content (%)
1	81.75 (0.483)	595 (16.725)	155 (4.46)	65 (5.49)	9.90 (0.0172)
2	79.29 (0.483)	615 (16.725)	145 (4.46)	45 (5.49)	10.25 (0.0172)
3	79.29 (0.483)	540 (16.725)	150 (4.46)	45 (5.46)	9.98 (0.0172)

Results from the mechanical damage evaluation are shown in Table 3 and Table 4 for each combine harvester unloading auger timing treatment for corn and soybeans, respectively. Data from each replication is shown in appendix C-2.

Table 3. Percentages of corn mechanical damage fractions (severe damage, minor damage and broken corn) from each combine harvester unloading auger system timing treatment. Averaged over the two samples for each rep in each timing treatment.

Timing		Severe Damage		Minor Damage		BC	
		Average	Std. Error	Average	Std. Error	Average	Std. Error
1*	Pre-Treatment	12.07%	1.00	6.86%	0.93	0.07%	0.03
	Post-Treatment	10.59%	1.98	4.03%	1.01	0.21%	0.16
	Difference	0.471%	1.05	-0.21%	1.00	0.18%	0.16
2	Pre-Treatment	12.65%	1.02	5.40%	2.04	0.84%	0.53
	Post-Treatment	12.25%	0.99	4.86%	1.51	0.90%	0.55
	Difference	-0.40%	0.91	-0.54%	0.86	0.06%	0.14
3	Pre-Treatment	11.17%	0.94	5.07%	0.47	0.16%	0.06
	Post-Treatment	11.75%	0.64	4.07%	0.52	0.18%	0.10
	Difference	0.58%	0.91	-0.99%	0.86	0.02%	0.14

* data only available for three reps in this treatment

Table 4. Percentage of soybeans (by number) that were damaged but unbroken for each timing. Averaged over the two samples for each rep in each timing treatment.

Timing		Damaged but unbroken	
		Average	Std. Error
1	Pre-Treatment	19.75%	2.16
	Post-Treatment	19.88%	2.04
	Difference	0.125%	2.06
2	Pre-Treatment	21.13%	3.79
	Post-Treatment	19.94%	3.07
	Difference	-1.19%	2.06
3	Pre-Treatment	18.18%	3.09
	Post-Treatment	18.50%	1.09
	Difference	0.37%	2.06

Since this experiment used dried stored grain harvested the previous year, it is conceivable that this factor alone could have influenced any of the response variables in the experiment. Hall and Johnson (1970) reported that corn below 20 to 24% moisture content will have an increase in damage. Hall (1974) said that soybeans below 13% are brittle and very susceptible to damage. If this is so then running the experiment with dried grains would then only amplify the amount of mechanical damage inflicted, resulting in a better resolution.

There was not a statistical difference in damage to either grain from timing to timing. While it can be criticized that the damage samples were quite small (100 grams) in relation to the amount of grain used for each replication (≈ 100 bushel) the standard errors are small compared to the means.

The statistical analyses showed almost no significant difference in mechanical damage between the pre- and post-treatment samples. The only difference that was significant was that the minor damage portion of the post-treatment samples in corn was less than pre-treatment samples! While the standard errors of the damage are low compared to the means, the amount of damage (means) is high, and the standard errors are about the same size as the differences among treatments. This comparable size of the differences and standard error of mechanical damage limited our ability to detect significant differences in mechanical damage among the unloading auger timing treatments.

The ISO Standard (ISO, 1999) was not followed exactly as it described for taking a flow rate measurement. The combine harvester's grain tank was filled using an auger separate of the combine harvester, not by means of its own loading system. The flow rate was recorded using soybeans and corn instead of wheat. This could be part of the reason why manufacturer's advertised flow rate were not achieved. Also the unloading auger drive shaft speed did not match the manufacturer's specifications. The standard uses 30 seconds of diverted flow into a collection area for the flow rate calculation, while the time for diverted flow in our test varied between 22-24 seconds.

Mean differences between the three timings were estimated for each response variable, and Fishers protected LSD was used to determine if pairs of timings were significantly different. For each mean comparison an $\alpha = 0.1$ was used. The larger significance level was used due to a rather small sample size, as well as concern about making a Type 2 error (not detecting a difference when there is one).

There were no differences in grain quality between treatments for corn or soybeans. The only significant difference was in the minor damage in corn, after treatment (4.3%) lower than before treatment (5.6%). This should not happen unless the decrease in minor damage is a result of increase in severe or broken, but these parameters showed no significant difference.

From the SAS program output it was determined that there were not significant interactions between timing treatment and grain for maximum startup torque, average operating torque, and flow rate (Appendix D). Interactions were detected between grain and timing treatment with moisture content, number of operating torque values, and standard deviation of operating torques (Table 5).

Table 5. Response variables that showed significant interactions between grain and timing.

Response Variable	Significant Interaction	Pr > F
Standard Deviation of Operating Torque	Grain and Timing	0.0539
Number of Operating Torque Values	Grain and Timing	0.0028
Moisture Content	Grain and Timing	0.0531

It was determined that the interaction effects for moisture content were not a relevant factor to the analysis since each grain type was stored at a different moisture content. The significant interaction of the number of operating torque values resulted due to several poor sets of data that had to have significant numbers of data points removed from the analysis for timing 3 in soybeans. Since there was also a significant difference between the standard deviation of operating torque for timings 1 and 3 we were somewhat skeptical about reaching a conclusion using the operating torque data for timing 3. However there were no statistical differences between the average operating torques (150 N·m) for any of the timings, and timing 2 for soybeans (similar to timing 3 for soybeans) also had a lower standard deviation of the operating torque (by 18 N·m). This gave us greater confidence that the data for timing 3 still accurately described the operating torque.

In soybeans alone auger timing 3 also had the smallest standard deviation of the operating torque (smallest variation from mean) 20.8 N·m (15.34 ft·lb) or about 30% less than timing 1. At timing 1 the end paddles of the cross augers are pushing grain towards the leading edge of the vertical auger as it pushes the grain up. As the ends of these augers come together, they are pinching the grain between them, possibly causing the higher peak torque at these times, and lower minimum toque at other times. This would result in a high variation in torque, leading to a high standard deviation of the operating torque. The end paddles of the cross augers in timing 3 do not push the bulk amount of grain to the vertical auger until the leading edge of the vertical auger is 90° past the cross auger. This would prevent the augers from pushing against each other as much, thereby reducing the peak torque, but also increasing the minimum torque leading to a lower standard deviation of the operating torque. Table 6 shows estimates of the difference from the statistical analysis.

Table 6. Significant differences that were in the same grain and showed a significant interaction.

Response Variable	Test of Difference Between	P > |t|	Estimate from Difference of Least Square Means (standard error)
Standard Deviation of the Operating Torque (N·m)	Soybeans Timing 1 and Soybeans Timing 2	0.0271	18.700 (7.7702)
	Soybeans Timing 1 and Soybeans Timing 3	0.0154	20.800 (7.7702)

Significant differences were found in both grains for the maximum startup torque between timings 1 and 3 and timings 2 and 3. Timings 1 and 2 averaged

10% greater startup torque (615 N·m) than timing 3 (558 N·m). While this is significant it should be noted that maximum startup torque is only one value from each of the four repetitions, not an average. It is also not known how far the grain has moved through the unloading augers when the maximum torque values were recorded. It is possible that each of the three timings would result in the grain being in a different location in the unloading auger when the peak startup torque was recorded.

Roughly 0.5 second passed from the time torque started to increase (shaft starting to rotate) to when peak startup torque was recorded. This would mean the augers rotate about 5 times before peak startup torque is recorded, however this is assuming no slippage on the v-belt pulley or the chain.

Significant differences were found in the unloading auger flow rate between timings 1 and 2 and timings 1 and 3. Although these differences were significant, the estimates of the differences between the least square means were 2.4 L/s (0.068 bu/s) and 2.2L/s (0.063 bu/s) respectively. In other words there was less than a 2.4 L/s (0.068 bu/s) flow rate difference in the timings, or about 3% difference from highest flow rate recorded from timing 1. This led to the determination that auger timing did not have a practically significant effect on flow rate. Shown in table 7 are the estimates of the differences from the statistical analysis.

Table 7. Response variables for which statistical analyses indicated significant differences for both grain types.

Response Variable	Test of Difference Between	P > |t|	Estimate from Difference of Least Square Means (standard error)
Max. Startup Torque (N·m)	Timing 1 and Timing 3	0.0503	60.7750 (28.9692)
	Timing 2 and Timing 3	0.0726	55.2375 (28.9692)
Flow Rate (L/s)	Timing 1 and Timing 2	0.0140	2.3892 (0.8725)
	Timing 1 and Timing 3	0.0171	2.2165 (0.8383)
Moisture Content (% w.b.)	Corn and Soybeans	<.0001	2.4500 (0.1409)

Conclusions

There were significant effects of auger timing on grain flow rate, torque and mechanical damage. For both corn and soybeans auger timing 3 (90° out of time) appeared to be the best overall setting. Specific conclusions were:

1. The manufacturer's suggested setting (timing 1) proved to be the best setting for the flow rate, however the difference was less than 2.5 L/s (0.07 bu/s) or about a 3% difference over timing 2 and timing 3.
2. Timings 1 and 2 averaged 10% greater startup torque (615 N·m) than timing 3 (558 N·m).
3. The average operating torque (150 N·m) did not significantly differ among any of the timing and grain combinations.
4. For soybeans timing 3 also had the lowest standard deviation in torque, 20 N·m (about 30%) less than timing 1. It should also be noted that timing 2 had a standard deviation of operating torque that was18 N·m less than

timing 1. There was no significant difference in the standard deviation of operating torque for corn.

5. There was an interaction of grain type with timing level for standard deviation of operating torque, number of operating torque values and moisture content.
6. We were unable to detect any differences in mechanical damage to corn or soybeans as a result of unloading auger timing.

Recommendations for Further Research

Several areas are suggested for further research. The three timings used in this study were chosen as a place to begin to evaluate the effects of unloading auger timing. Timing 3, with the horizontal cross augers timed 90° behind the vertical auger, seemed to have the best all around performance in this study. It would be interesting to see how the performance of the unloading auger system changes when the cross augers are timed 90° ahead of the vertical auger and 45° before and after the vertical auger. It would also be interesting to have a comparison to this study using grain at harvest level moisture contents.

References

Al-Mosawi, A.A. 1983. Corn kernel damage in harvesting and on farm handling system. Masters Thesis. University of Nebraska Lincoln

ASAE. 2000a. ASAE Standard EP389.2: Auger Flighting Design Considerations. ASAE, St.Joseph, MI. pp. 241-242.

ASAE. 2000b. ASAE Standard D245.5: Moisture Relationships of Plant-based Agricultural Products. ASAE, St.Joseph, MI. pp. 508-524.

Caterpillar. 1998 Operation and Maintenance Manual, Lexion 460 and Lexion 465 Combines. SEBU7119. pp 434-435.

Chang, C.S. and J.L. Steele. 1995. Performance characteristics of the inlet section of a screw conveyor. *Transactions of the ASAE* 13(5):627-630.

Chowdhury, M.H. and W.F. Buchele. 1975. Colorimetric determination of grain damage. ASAE Paper No. 75-1538, ASAE, St.Joseph, MI 49085

Fernando, S.D. 2001. Design and development of an alternative soybean harvester. Masters Thesis. University of Nebraska Lincoln

Hall, G.E. and W.H. Johnson. 1970. Corn kernel crackage induced by mechanical shelling. *Transactions of the ASAE* 13(1):51-55.

Hall, G.E. 1974. Damage during handling of shelled corn and soybeans. *Transactions of the ASAE* 17(2):335-338.

ISO Standards. 1999. ISO 5687: Equipment for harvesting — Combine harvesters — Determination and designation of grain tank capacity and unloading device performance. Genève, Switzerland. ISO 5687:1999(E).

Midwest Plan Service. 1988. Grain drying, handling, and storage handbook. MWPS-13. Midwest Plan Service, Ames,IA.

Paulsen, M.R. and W.R. Nave. 1977. Soybean seed coat damage detection methods. ASAE Paper No. 77-3503, ASAE, St.Joseph, MI 49085.

Pierce, R.O. and M.A. Hanna. 1985 Corn kernel damage during on-farm handling. *Transactions of the ASAE* 28(1):239-241, 245.

Pierce, R.O., K.L.Salter, and D. Jones. 1991. On-farm broken corn levels. *Applied Engineering in Agriculture* 7(6)741-745.

Rodda, E.D., M.P. Steinberg, and L.S. Wei. 1973. Soybean damage detection and evaluation for food use. Transactions of the ASAE 16(2):365-366.

Sands, L.D. and G.E. Hall. 1971. Damage to shelled corn during transport in a screw conveyor. *Transactions of the ASAE* 14(3):584-585, 589.

SAS Institute, Inc. 2000 SAS OnlineDoc, Version 8. Cary NC: SAS Institute.

USDA. 1996. Grain Inspection Packers and Stockyards Association. Online. Official United States Standards, Corn. 1996. Available at http://www.usda.gov/gipsa/reference-library/standards/standards/.htm Accessed on 11/18/2002.

Appendix A

Program for the TFX-11 data acquisition computer used for collecting torque data, shaft speed (RPM), and to operate the directional control valve for the grain diverter.

```
// Program LexnTest.TFB for collection of unloading system torque
// and speed data using the onset TFX-11 computer.
pclr 0,1,2
pset 3,4,5,6,7,16,17,18,19,20,21,22,23

INIT:        INPUT "The year is (20??) "?(5)
      INPUT "The month is (1 to 12)"?(4)
      INPUT "The day is (1 to 31)" ?(3)
      INPUT "The hour is (0 to 23)"?(2)
      INPUT "The minute is (0 to 59)" ?(1)
      STIME        //set TFX-11 clock
      RTIME              //read TFX-11 clock time
      PRINT "The current time is ",?(2),":",?(1),":",?(0);
      PRINT " on ",?(4),"/",?(3),"/",?(5),"."
      PRINT
      INPUT "Is this correct(0)for no, or(1)for yes."A
      IF A=0       //go back to get correct date/time if answer is no.
      GOTO INIT
      ENDIF

      PRINT
      PRINT "Prepare combine and system to start the test."
      PRINT "Click button to start the unloading auger and the data"
      PRINT "collection start switch simultaneously when ready to
begin"
      PRINT "data collection and take samples."

S1:   A1= PIN(1) //check to see if data collection start switch has
been clicked.
      IF A1 <>2    // if it hasn't
      GOTO S1            //go back and check again.
      ENDIF        //if it has, go on
      RTIME        //read start time
      STORE  STR(\34,?(2),":",?(1),":",?(0),\34,"
",\34,?(4),"/",?(3),"/",?(5),\34,\13,\10)
      RATE 1             //leave timing speed at 100 counts per second.
      SLEEP 0            //start timing
      SLEEP 450    //delay 4.5 seconds
        SLEEP 0
      FOR I=1 to 201     //collect 201 torque values in Nm at 0.01
second intervals
        SLEEP 1
      T!=0.029524*FLOAT(CHAN(0))-46.6734
      STORE STR(#7.1F,T!,\13,\10) //store startup torque data
      NEXT I
      PRINT T!
```

Program for the TFX-11 data acquisition computer – continued

```
      F!=0.
      TIM=PERIOD (40,40)  //measure time to get 40 teeth on drive shaft
sprocket (about 0.1s)
      IF TIM = 0
      GOTO S2
      ENDIF
      F!= 393216000./FLOAT(TIM)  //convert time to shaft speed in rpm.
S2:   STORE STR(#8.2F,F!,\13,\10)  //store startup speed data
      PRINT F!

      SLEEP 0           //restart timing
      SLEEP 600   //wait 6 seconds for flow to stabilize

      PSET 2      //activate relay (solenoid) to extend pneumatic
cylinder (start grain collection)
      SLEEP 1150  // wait 11.5 seconds
        SLEEP 0
      FOR I=1 to 101    //collect 101 torque values (in Nm) at 0.01
second intervals
        SLEEP 1
      T!=0.029524*FLOAT(CHAN(0))-46.6734
      STORE STR (#7.1F,T!,\13,\10)  //store normal torque data
      NEXT I
      F!=0.
      TIM= PERIOD (400,300)   //measure time for 400 teeth on drive
shaft sprocket to pass sensor (about 1s)
      IF TIM=0
      GOTO S3
      ENDIF
      F!= 3932160000./FLOAT (TIM)

S3:   STORE STR(#8.2F,F!,\13,\10)
      SLEEP 1150  //wait another 11.5 seconds
      PCLR 2            //shut off relay (solenoid) so cylinder
retracts
                  //(ends grain collection of about 30 seconds.)
      STOP
```

Appendix B

The timing and grain treatment combinations were randomized and applied during the experiment in the order shown below.

Replication	Grain	Timing
1	CORN	2
1	CORN	1
2	CORN	1
1	CORN	3
2	CORN	3
3	CORN	1
3	CORN	3
2	CORN	2
4	CORN	1
3	CORN	2
4	CORN	3
4	CORN	2
1	SOYBEANS	2
1	SOYBEANS	1
2	SOYBEANS	2
2	SOYBEANS	1
1	SOYBEANS	3
2	SOYBEANS	3
3	SOYBEANS	1
3	SOYBEANS	3
4	SOYBEANS	3
4	SOYBEANS	1
3	SOYBEANS	2
4	SOYBEANS	2

Appendix C-1

Performance data was collected as described in the procedures. The maximum startup torque, average operating torque, standard deviation of the operating torque, number of operating torque values, flow rate, and moisture content for each treatment are given.

Rep	Grain	Timing	Max. Startup Torque (N·m)	Avg. Operating Torque (N·m)	Std. Dev. of Operating Torque (N·m)	Flow Rate (L/s)	Moisture Content %	No. Of Operating Torque Values
1	Corn	1	585	145	43	87.4	12.4	100
2	Corn	1	680	130	39	87.6	12.9	98
3	Corn	1	575	150	45	88.3	12.9	101
4	Corn	1	735	150	47	93.8	12.2	70
1	Corn	2	595	150	41	86.5	12.8	101
2	Corn	2	690	155	44	no data	12.3	82
3	Corn	2	560	150	58	87.4	11.5	62
4	Corn	2	595	130	39	86.7	12.1	90
1	Corn	3	610	140	41	87.3	12.9	100
2	Corn	3	585	200	51	87.5	12.4	78
3	Corn	3	620	155	44	88.6	12.9	98
4	Corn	3	495	135	67	85.7	12.6	70

Rep	Grain	Timing	Max. Startup Torque (N·m)	Avg. Operating Torque (N·m)	Std. Dev. of Operating Torque (N·m)	Flow Rate (L/s)	Moisture Content %	No. Of Operating Torque Values
1	Soybeans	1	575	160	86	80.8	9.7	77
2	Soybeans	1	655	160	80	81.9	9.7	88
3	Soybeans	1	600	170	50	81.0	10.2	100
4	Soybeans	1	550	140	41	83.2	10	101
1	Soybeans	2	525	145	43	79.1	10.7	101
2	Soybeans	2	615	155	45	80.0	9.8	88
3	Soybeans	2	660	140	46	79.4	10.3	101
4	Soybeans	2	670	140	49	79.0	10.2	64
1	Soybeans	3	550	155	47	77.7	9.8	64
2	Soybeans	3	485	135	45	77.6	10.2	23
3	Soybeans	3	570	160	36	80.5	10.1	16
4	Soybeans	3	550	155	47	81.3	9.8	16

Appendix C-2

Differences in percentages of corn mechanical damage fractions (severe damage, minor damage and broken corn) from each combine harvester unloading auger system timing treatment. Values shown are averages over the two samples for each rep. Calculated by subtracting the pre-treatment damage percentage of from the post-treatment damage percentage.

Timing	Rep	Severe Damage	Minor Damage	BC
1	1	-0.31%	-2.30%	0.70%
1	2	1.61%	-1.73%	-0.10%
1	3	0.11%	-2.42%	-0.05%
1	4	no data	no data	no data
2	1	-0.27%	-3.16%	0.14%
2	2	-0.25%	2.45%	0.19%
2	3	-0.41%	-0.21%	-0.27%
2	4	-0.68%	-1.26%	0.19%
3	1	1.07%	0.34%	-0.25%
3	2	4.35%	-2.20%	-0.05%
3	3	-2.34%	0.38%	0.20%
3	4	-0.77%	-2.50%	0.19%

Differences in percentage of soybeans (by number) that were damaged but unbroken for each timing and replication. Values shown are averages over the two samples for each rep. Calculated by subtracting the number of enlarged beans in the pre-treatment sample from the post-treatment sample.

Timing	Rep	Damaged but unbroken (# out of 100 whole beans)
1	1	0.25
1	2	1
1	3	0
1	4	-0.75
2	1	0.25
2	2	7.5
2	3	-6.5
2	4	-6
3	1	-2.5
3	2	3.25
3	3	2.25
3	4	-1.5

Appendix D

This appendix includes the glossary of terms, programs and output from the SAS system (The SAS System for Windows, v8.00. SAS Institute Inc. Cary, NC) for each response variable used in the analysis.

Glossary of Terms

Appendix D-1 shows the program used for the comparisons of torque, flow rate and moisture content.

Appendix D-2 shows the output from the comparisons of torque, flow rate and moisture content.

Appendix D-3 shows the program used for the comparisons of mechanical damage with corn.

Appendix D-4 shows the output from the comparisons of mechanical damage with corn.

Appendix D-5 shows the program used for the comparisons of mechanical damage with soybeans.

Appendix D-6 shows the output from the comparison of mechanical damage with soybeans.

Glossary of Terms

Abbreviations were used for the statistical analysis program. The abbreviations, their definitions and the units for the quantities are shown below.

maxstart	Maximum startup torque in N·m
avgrun	Average operating torque in N·m
sdrun	Standard Deviation of operating torque in N·m
flow	Flow rate of the unloading system in bushels per second
mc	Moisture content of the grain in percent wet basis
numop	Number of operating torque values used in the analysis
befaft	Indicates whether the sample was taken from before or after the grain was run through unloading system (1= before and 2= after)
severe	Percentage of corn with severe damage
minor	Percentage of corn with minor damage
bcfm	Percentage of corn that was considered as broken
damage	Percentage (number out of 100) of soybeans that were damaged but un broken
timing	Unloading auger position (1-3)
rep	Replication (1-4)

Appendix D-1

```
data performance;
  input rep grain $ timing maxstart avgrun sdrun flow mc numop;
    datalines;

1  Corn  1  583.5  144.1  43.8  2.480  12.4  100
2  Corn  1  679.4  131.1  39.2  2.487  12.9  98
3  Corn  1  574.5  151.7  45.4  2.505  12.9  101
4  Corn  1  735.1  149.4  46.8  2.661  12.2  70
1  Corn  2  593.9  150.7  40.9  2.454  12.8  101
2  Corn  2  690.2  156.9  44.1  .      12.3  82
3  Corn  2  559.9  149.2  58.1  2.480  11.5  62
4  Corn  2  593.9  132.5  38.8  2.459  12.1  90
1  Corn  3  608.5  138.0  41.2  2.477  12.9  100
2  Corn  3  584.4  201.0  50.9  2.484  12.4  78
3  Corn  3  620.8  155.1  44.1  2.515  12.9  98
4  Corn  3  497.0  137.5  67.4  2.432  12.6  70

1  Soybeans  1  576.9  159.4  85.5  2.293  9.7   77
2  Soybeans  1  654.3  159.6  80.3  2.323  9.7   88
3  Soybeans  1  598.1  170.2  50.8  2.299  10.2  100
4  Soybeans  1  550.9  141.2  41.4  2.362  10    101
1  Soybeans  2  523.5  146.0  43.4  2.245  10.7  101
2  Soybeans  2  617.0  155.1  44.5  2.271  9.8   88
3  Soybeans  2  659.1  139.2  46.4  2.253  10.3  101
4  Soybeans  2  670.9  139.7  48.9  2.241  10.2  64
1  Soybeans  3  548.0  153.2  46.6  2.205  9.8   64
2  Soybeans  3  484.3  133.8  45.3  2.201  10.2  23
3  Soybeans  3  572.6  161.2  36.4  2.285  10.1  16
4  Soybeans  3  550.9  156.9  46.5  2.308  9.8   16

proc print data=performance;
run;

proc mixed data=performance;
  class grain timing;
  model maxstart=grain timing grain*timing;
  lsmeans grain timing/diff;
run;

proc mixed data=performance;
  class grain timing;
  model avgrun=grain timing grain*timing;
  lsmeans grain timing/diff;
run;
```

SAS program – continued

```
proc mixed data=performance;
  class grain timing;
  model sdrun=grain timing grain*timing;
  lsmeans grain*timing/diff;
run;

proc mixed data=performance;
  class grain timing;
  model flow=grain timing grain*timing;
  lsmeans grain timing/diff;
run;

proc mixed data=performance;
  class grain timing;
  model mc=grain timing grain*timing;
  lsmeans grain*timing/diff;
run;

proc mixed data=performance;
  class grain timing;
  model numop=grain timing grain*timing;
  lsmeans grain*timing/diff;
run;
```

Appendix D-2

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The Mixed Procedure

Model Information

Data Set	WORK.PERFORMANCE
Dependent Variable	maxstart
Covariance Structure	Diagonal
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Residual

Class Level Information

Class	Levels	Values
grain	2	Corn Soybeans
timing	3	1 2 3

Dimensions

Covariance Parameters	1
Columns in X	12
Columns in Z	0
Subjects	1
Max Obs Per Subject	24
Observations Used	24
Observations Not Used	0
Total Observations	24

Covariance Parameter Estimates

Cov Parm	Estimate
Residual	3356.85

Fit Statistics

-2 Res Log Likelihood	205.5
AIC (smaller is better)	207.5
AICC (smaller is better)	207.8
BIC (smaller is better)	208.4

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The Mixed Procedure

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
grain	1	18	1.23	0.2823
timing	2	18	2.69	0.0949
grain*timing	2	18	0.54	0.5915

Least Squares Means

Effect	grain	timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		610.09	16.7254	18	36.48	<.0001
grain	Soybeans		583.87	16.7254	18	34.91	<.0001
timing		1	619.09	20.4843	18	30.22	<.0001
timing		2	613.55	20.4843	18	29.95	<.0001
timing		3	558.31	20.4843	18	27.26	<.0001

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		26.2167	23.6532	18	1.11	0.2823
timing		1		2	5.5375	28.9692	18	0.19	0.8505
timing		1		3	60.7750	28.9692	18	2.10	0.0503
timing		2		3	55.2375	28.9692	18	1.91	0.0726

SAS output – continued

```
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                 The Mixed Procedure

                  Model Information

Data Set                     WORK.PERFORMANCE
Dependent Variable           avgrun
Covariance Structure         Diagonal
Estimation Method            REML
Residual Variance Method     Profile
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Residual


               Class Level Information

 Class      Levels    Values

 grain           2    Corn Soybeans
 timing          3    1 2 3


                     Dimensions

          Covariance Parameters             1
          Columns in X                     12
          Columns in Z                      0
          Subjects                          1
          Max Obs Per Subject              24
          Observations Used                24
          Observations Not Used             0
          Total Observations               24


                Covariance Parameter
                      Estimates

                Cov Parm      Estimate

                Residual        238.76


                   Fit Statistics

         -2 Res Log Likelihood          158.0
         AIC (smaller is better)        160.0
         AICC (smaller is better)       160.2
         BIC (smaller is better)        160.8

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                 The Mixed Procedure

            Type 3 Tests of Fixed Effects

                  Num     Den
 Effect            DF      DF    F Value    Pr > F

 grain              1      18       0.06    0.8117
 timing             2      18       0.60    0.5610
 grain*timing       2      18       0.94    0.4077
```

SAS output – continued

Least Squares Means

Effect	grain	timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		149.77	4.4606	18	33.58	<.0001
grain	Soybeans		151.29	4.4606	18	33.92	<.0001
timing		1	150.84	5.4631	18	27.61	<.0001
timing		2	146.16	5.4631	18	26.75	<.0001
timing		3	154.59	5.4631	18	28.30	<.0001

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		-1.5250	6.3083	18	-0.24	0.8117
timing		1		2	4.6750	7.7260	18	0.61	0.5527
timing		1		3	-3.7500	7.7260	18	-0.49	0.6333
timing		2		3	-8.4250	7.7260	18	-1.09	0.2899

SAS output – continued

```
The SAS System          14:02 Friday, October 4, 2002  12

                    The Mixed Procedure

                     Model Information

Data Set                        WORK.PERFORMANCE
Dependent Variable              sdrun
Covariance Structure            Diagonal
Estimation Method               REML
Residual Variance Method        Profile
Fixed Effects SE Method         Model-Based
Degrees of Freedom Method       Residual

                 Class Level Information

  Class       Levels     Values

  grain          2       Corn Soybeans
  timing         3       1 2 3

                       Dimensions

          Covariance Parameters            1
          Columns in X                    12
          Columns in Z                     0
          Subjects                         1
          Max Obs Per Subject             24
          Observations Used               24
          Observations Not Used            0
          Total Observations              24

                 Covariance Parameter
                       Estimates

                 Cov Parm      Estimate

                 Residual        120.75

                      Fit Statistics

        -2 Res Log Likelihood           145.7
        AIC (smaller is better)         147.7
        AICC (smaller is better)        147.9
        BIC (smaller is better)         148.6

                 The SAS System          14:02 Friday, October 4, 2002  13

                The Mixed Procedure

            Type 3 Tests of Fixed Effects

                      Num      Den
  Effect               DF       DF    F Value     Pr > F

  grain                 1       18       1.06     0.3179
  timing                2       18       1.35     0.2846
  grain*timing          2       18       3.45     0.0539

                 Least Squares Means

                                             Standard
Effect     grain       timing    Estimate       Error     DF    t Value    Pr > |t|

grain      Corn                   46.7250      3.1722     18      14.73      <.0001
grain      Soybeans               51.3333      3.1722     18      16.18      <.0001
timing                   1        54.1500      3.8851     18      13.94      <.0001
timing                   2        45.6375      3.8851     18      11.75      <.0001
timing                   3        47.3000      3.8851     18      12.17      <.0001
```

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		-4.6083	4.4861	18	-1.03	0.3179
timing		1		2	8.5125	5.4944	18	1.55	0.1387
timing		1		3	6.8500	5.4944	18	1.25	0.2285
timing		2		3	-1.6625	5.4944	18	-0.30	0.7657

SAS output – continued

```
The SAS System        14:02 Friday, October 4, 2002  14

                  The Mixed Procedure

                  Model Information

Data Set                      WORK.PERFORMANCE
Dependent Variable            flow
Covariance Structure          Diagonal
Estimation Method             REML
Residual Variance Method      Profile
Fixed Effects SE Method       Model-Based
Degrees of Freedom Method     Residual

              Class Level Information

 Class      Levels     Values

 grain           2     Corn Soybeans
 timing          3     1 2 3

                   Dimensions

        Covariance Parameters            1
        Columns in X                    12
        Columns in Z                     0
        Subjects                         1
        Max Obs Per Subject             24
        Observations Used               23
        Observations Not Used            1
        Total Observations              24

              Covariance Parameter
                    Estimates

              Cov Parm      Estimate

              Residual      0.002263

                 Fit Statistics

       -2 Res Log Likelihood           -47.3
       AIC (smaller is better)         -45.3
       AICC (smaller is better)        -45.0
       BIC (smaller is better)         -44.4
```

```
                  The SAS System        14:02 Friday, October 4, 2002  15

                 The Mixed Procedure

            Type 3 Tests of Fixed Effects

                       Num      Den
  Effect                DF       DF    F Value     Pr > F

  grain                  1       17     119.02     <.0001
  timing                 2       17       4.90     0.0209
  grain*timing           2       17       0.06     0.9426

                 Least Squares Means

                                          Standard
Effect    grain       timing   Estimate      Error      DF    t Value    Pr > |t|

grain     Corn                   2.4915    0.01448      17     172.11      <.0001
grain     Soybeans               2.2738    0.01373      17     165.56      <.0001
timing                 1         2.4263    0.01682      17     144.24      <.0001
timing                 2         2.3584    0.01817      17     129.81      <.0001
timing                 3         2.3634    0.01682      17     140.51      <.0001
```

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		0.2177	0.01995	17	10.91	<.0001
timing		1		2	0.06783	0.02476	17	2.74	0.0140
timing		1		3	0.06288	0.02379	17	2.64	0.0171
timing		2		3	-0.00496	0.02476	17	-0.20	0.8437

SAS output – continued

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The Mixed Procedure

Model Information

Data Set	WORK.PERFORMANCE
Dependent Variable	mc
Covariance Structure	Diagonal
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Residual

Class Level Information

Class	Levels	Values
grain	2	Corn Soybeans
timing	3	1 2 3

Dimensions

Covariance Parameters	1
Columns in X	12
Columns in Z	0
Subjects	1
Max Obs Per Subject	24
Observations Used	24
Observations Not Used	0
Total Observations	24

Covariance Parameter Estimates

Cov Parm	Estimate
Residual	0.1192

Fit Statistics

-2 Res Log Likelihood	21.1
AIC (smaller is better)	23.1
AICC (smaller is better)	23.4
BIC (smaller is better)	24.0

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The Mixed Procedure

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
grain	1	18	302.22	<.0001
timing	2	18	0.28	0.7618
grain*timing	2	18	3.47	0.0531

Least Squares Means

Effect	grain	timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		12.4917	0.09965	18	125.35	<.0001
grain	Soybeans		10.0417	0.09965	18	100.77	<.0001
timing		1	11.2500	0.1220	18	92.18	<.0001
timing		2	11.2125	0.1220	18	91.87	<.0001
timing		3	11.3375	0.1220	18	92.89	<.0001

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		2.4500	0.1409	18	17.38	<.0001
timing		1		2	0.03750	0.1726	18	0.22	0.8304
timing		1		3	-0.08750	0.1726	18	-0.51	0.6183
timing		2		3	-0.1250	0.1726	18	-0.72	0.4782

SAS output – continued

```
The SAS System          14:02 Friday, October 4, 2002  18

                    The Mixed Procedure

                     Model Information

Data Set                          WORK.PERFORMANCE
Dependent Variable                numop
Covariance Structure              Diagonal
Estimation Method                 REML
Residual Variance Method          Profile
Fixed Effects SE Method           Model-Based
Degrees of Freedom Method         Residual


                 Class Level Information

  Class      Levels     Values

  grain           2     Corn Soybeans
  timing          3     1 2 3


                        Dimensions

           Covariance Parameters              1
           Columns in X                      12
           Columns in Z                       0
           Subjects                           1
           Max Obs Per Subject               24
           Observations Used                 24
           Observations Not Used              0
           Total Observations                24


                  Covariance Parameter
                        Estimates

                  Cov Parm      Estimate

                  Residual        279.51


                      Fit Statistics

          -2 Res Log Likelihood           160.8
          AIC (smaller is better)         162.8
          AICC (smaller is better)        163.0
          BIC (smaller is better)         163.7

                      The SAS System        14:02 Friday, October 4, 2002  19

                    The Mixed Procedure

               Type 3 Tests of Fixed Effects

                       Num      Den
  Effect                DF       DF    F Value    Pr > F

  grain                  1       18       6.64    0.0190
  timing                 2       18       9.33    0.0017
  grain*timing           2       18       8.29    0.0028


                    Least Squares Means

                                                 Standard
Effect      grain        timing    Estimate       Error       DF    t Value    Pr > |t|

grain       Corn                    87.5000      4.8263       18      18.13      <.0001
grain       Soybeans                69.9167      4.8263       18      14.49      <.0001
timing                     1        91.8750      5.9109       18      15.54      <.0001
timing                     2        86.1250      5.9109       18      14.57      <.0001
timing                     3        58.1250      5.9109       18       9.83      <.0001
```

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain	Corn		Soybeans		17.5833	6.8254	18	2.58	0.0190
timing		1		2	5.7500	8.3593	18	0.69	0.5003
timing		1		3	33.7500	8.3593	18	4.04	0.0008
timing		2		3	28.0000	8.3593	18	3.35	0.0036

SAS output – continued

```
The SAS System        14:02 Friday, October 4, 2002  20

                 The Mixed Procedure

                  Model Information

Data Set                     WORK.PERFORMANCE
Dependent Variable           sdrun
Covariance Structure         Diagonal
Estimation Method            REML
Residual Variance Method     Profile
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Residual


              Class Level Information

 Class     Levels    Values

 grain          2    Corn Soybeans
 timing         3    1 2 3


                     Dimensions

         Covariance Parameters              1
         Columns in X                      12
         Columns in Z                       0
         Subjects                           1
         Max Obs Per Subject               24
         Observations Used                 24
         Observations Not Used              0
         Total Observations                24


                Covariance Parameter
                     Estimates

                Cov Parm      Estimate

                Residual        120.75


                   Fit Statistics

        -2 Res Log Likelihood            145.7
        AIC (smaller is better)          147.7
        AICC (smaller is better)         147.9
        BIC (smaller is better)          148.6
```

```
                 The SAS System        14:02 Friday, October 4, 2002  21

                The Mixed Procedure

            Type 3 Tests of Fixed Effects

                   Num     Den
 Effect             DF      DF    F Value    Pr > F

 grain               1      18       1.06    0.3179
 timing              2      18       1.35    0.2846
 grain*timing        2      18       3.45    0.0539


                 Least Squares Means

                                            Standard
Effect         grain      timing   Estimate     Error    DF   t Value   Pr > |t|

grain*timing   Corn       1         43.8000    5.4944    18      7.97     <.0001
grain*timing   Corn       2         45.4750    5.4944    18      8.28     <.0001
grain*timing   Corn       3         50.9000    5.4944    18      9.26     <.0001
grain*timing   Soybeans   1         64.5000    5.4944    18     11.74     <.0001
grain*timing   Soybeans   2         45.8000    5.4944    18      8.34     <.0001
grain*timing   Soybeans   3         43.7000    5.4944    18      7.95     <.0001
```

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain*timing	Corn	1	Corn	2	-1.6750	7.7702	18	-0.22	0.8317
grain*timing	Corn	1	Corn	3	-7.1000	7.7702	18	-0.91	0.3729
grain*timing	Corn	1	Soybeans	1	-20.7000	7.7702	18	-2.66	0.0158
grain*timing	Corn	1	Soybeans	2	-2.0000	7.7702	18	-0.26	0.7998
grain*timing	Corn	1	Soybeans	3	0.1000	7.7702	18	0.01	0.9899
grain*timing	Corn	2	Corn	3	-5.4250	7.7702	18	-0.70	0.4940
grain*timing	Corn	2	Soybeans	1	-19.0250	7.7702	18	-2.45	0.0248
grain*timing	Corn	2	Soybeans	2	-0.3250	7.7702	18	-0.04	0.9671
grain*timing	Corn	2	Soybeans	3	1.7750	7.7702	18	0.23	0.8219
grain*timing	Corn	3	Soybeans	1	-13.6000	7.7702	18	-1.75	0.0971
grain*timing	Corn	3	Soybeans	2	5.1000	7.7702	18	0.66	0.5199
grain*timing	Corn	3	Soybeans	3	7.2000	7.7702	18	0.93	0.3664
grain*timing	Soybeans	1	Soybeans	2	18.7000	7.7702	18	2.41	0.0271
grain*timing	Soybeans	1	Soybeans	3	20.8000	7.7702	18	2.68	0.0154
grain*timing	Soybeans	2	Soybeans	3	2.1000	7.7702	18	0.27	0.7900

SAS output – continued

```
The SAS System          14:02 Friday, October 4, 2002  22

                    The Mixed Procedure

                    Model Information

Data Set                       WORK.PERFORMANCE
Dependent Variable             mc
Covariance Structure           Diagonal
Estimation Method              REML
Residual Variance Method       Profile
Fixed Effects SE Method        Model-Based
Degrees of Freedom Method      Residual

                 Class Level Information

 Class       Levels     Values

 grain            2     Corn Soybeans
 timing           3     1 2 3

                       Dimensions

          Covariance Parameters               1
          Columns in X                       12
          Columns in Z                        0
          Subjects                            1
          Max Obs Per Subject                24
          Observations Used                  24
          Observations Not Used               0
          Total Observations                 24

                 Covariance Parameter
                       Estimates

                 Cov Parm      Estimate

                 Residual        0.1192

                     Fit Statistics

         -2 Res Log Likelihood             21.1
         AIC (smaller is better)           23.1
         AICC (smaller is better)          23.4
         BIC (smaller is better)           24.0

                  The SAS System          14:02 Friday, October 4, 2002  23

                   The Mixed Procedure

              Type 3 Tests of Fixed Effects

                        Num      Den
 Effect                  DF       DF    F Value    Pr > F

 grain                    1       18     302.22    <.0001
 timing                   2       18       0.28    0.7618
 grain*timing             2       18       3.47    0.0531

                   Least Squares Means

                                                  Standard
Effect          grain       timing    Estimate       Error     DF    t Value    Pr > |t|

grain*timing    Corn        1          12.6000      0.1726     18      73.00      <.0001
grain*timing    Corn        2          12.1750      0.1726     18      70.54      <.0001
grain*timing    Corn        3          12.7000      0.1726     18      73.58      <.0001
grain*timing    Soybeans    1           9.9000      0.1726     18      57.36      <.0001
grain*timing    Soybeans    2          10.2500      0.1726     18      59.38      <.0001
grain*timing    Soybeans    3           9.9750      0.1726     18      57.79      <.0001
```

SAS output – continued

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain*timing	Corn	1	Corn	2	0.4250	0.2441	18	1.74	0.0987
grain*timing	Corn	1	Corn	3	-0.1000	0.2441	18	-0.41	0.6869
grain*timing	Corn	1	Soybeans	1	2.7000	0.2441	18	11.06	<.0001
grain*timing	Corn	1	Soybeans	2	2.3500	0.2441	18	9.63	<.0001
grain*timing	Corn	1	Soybeans	3	2.6250	0.2441	18	10.75	<.0001
grain*timing	Corn	2	Corn	3	-0.5250	0.2441	18	-2.15	0.0453
grain*timing	Corn	2	Soybeans	1	2.2750	0.2441	18	9.32	<.0001
grain*timing	Corn	2	Soybeans	2	1.9250	0.2441	18	7.89	<.0001
grain*timing	Corn	2	Soybeans	3	2.2000	0.2441	18	9.01	<.0001
grain*timing	Corn	3	Soybeans	1	2.8000	0.2441	18	11.47	<.0001
grain*timing	Corn	3	Soybeans	2	2.4500	0.2441	18	10.04	<.0001
grain*timing	Corn	3	Soybeans	3	2.7250	0.2441	18	11.16	<.0001
grain*timing	Soybeans	1	Soybeans	2	-0.3500	0.2441	18	-1.43	0.1688
grain*timing	Soybeans	1	Soybeans	3	-0.07500	0.2441	18	-0.31	0.7622
grain*timing	Soybeans	2	Soybeans	3	0.2750	0.2441	18	1.13	0.2747

SAS output – continued

```
The SAS System        14:02 Friday, October 4, 2002  24

                  The Mixed Procedure

                   Model Information

Data Set                     WORK.PERFORMANCE
Dependent Variable           numop
Covariance Structure         Diagonal
Estimation Method            REML
Residual Variance Method     Profile
Fixed Effects SE Method      Model-Based
Degrees of Freedom Method    Residual

                Class Level Information

 Class     Levels    Values

 grain          2    Corn Soybeans
 timing         3    1 2 3

                      Dimensions

        Covariance Parameters             1
        Columns in X                     12
        Columns in Z                      0
        Subjects                          1
        Max Obs Per Subject              24
        Observations Used                24
        Observations Not Used             0
        Total Observations               24

                Covariance Parameter
                     Estimates

                Cov Parm      Estimate

                Residual        279.51

                    Fit Statistics

       -2 Res Log Likelihood          160.8
       AIC (smaller is better)        162.8
       AICC (smaller is better)       163.0
       BIC (smaller is better)        163.7

                  The SAS System        14:02 Friday, October 4, 2002  25

                  The Mixed Procedure

             Type 3 Tests of Fixed Effects

                   Num      Den
Effect              DF       DF    F Value    Pr > F

grain                1       18       6.64    0.0190
timing               2       18       9.33    0.0017
grain*timing         2       18       8.29    0.0028
```

SAS output – continued

Least Squares Means

Effect	grain	timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain*timing	Corn	1	92.2500	8.3593	18	11.04	<.0001
grain*timing	Corn	2	83.7500	8.3593	18	10.02	<.0001
grain*timing	Corn	3	86.5000	8.3593	18	10.35	<.0001
grain*timing	Soybeans	1	91.5000	8.3593	18	10.95	<.0001
grain*timing	Soybeans	2	88.5000	8.3593	18	10.59	<.0001
grain*timing	Soybeans	3	29.7500	8.3593	18	3.56	0.0022

Differences of Least Squares Means

Effect	grain	timing	_grain	_timing	Estimate	Standard Error	DF	t Value	Pr > |t|
grain*timing	Corn	1	Corn	2	8.5000	11.8219	18	0.72	0.4814
grain*timing	Corn	1	Corn	3	5.7500	11.8219	18	0.49	0.6326
grain*timing	Corn	1	Soybeans	1	0.7500	11.8219	18	0.06	0.9501
grain*timing	Corn	1	Soybeans	2	3.7500	11.8219	18	0.32	0.7547
grain*timing	Corn	1	Soybeans	3	62.5000	11.8219	18	5.29	<.0001
grain*timing	Corn	2	Corn	3	-2.7500	11.8219	18	-0.23	0.8187
grain*timing	Corn	2	Soybeans	1	-7.7500	11.8219	18	-0.66	0.5204
grain*timing	Corn	2	Soybeans	2	-4.7500	11.8219	18	-0.40	0.6926
grain*timing	Corn	2	Soybeans	3	54.0000	11.8219	18	4.57	0.0002
grain*timing	Corn	3	Soybeans	1	-5.0000	11.8219	18	-0.42	0.6773
grain*timing	Corn	3	Soybeans	2	-2.0000	11.8219	18	-0.17	0.8675
grain*timing	Corn	3	Soybeans	3	56.7500	11.8219	18	4.80	0.0001
grain*timing	Soybeans	1	Soybeans	2	3.0000	11.8219	18	0.25	0.8026
grain*timing	Soybeans	1	Soybeans	3	61.7500	11.8219	18	5.22	<.0001
grain*timing	Soybeans	2	Soybeans	3	58.7500	11.8219	18	4.97	<.0001

Appendix D-3

```
data corndamage;
 input timing rep befaft severe minor bcfm;
 datalines;
 1  1  1  13.823  7.991   0
 1  1  2  13.514  5.692   .698
 1  2  1  10.358  7.592   .099
 1  2  2  11.968  5.866   0
 1  3  1  12.044  5.013   .099
 1  3  2  12.156  2.594   .050
 1  4  1  .       .       .
 1  4  2  4.719   1.986   .1
 2  1  1  10.350  11.486  2.413
 2  1  2  10.082  8.322   2.551
 2  2  1  12.101  4.039   .089
 2  2  2  11.856  6.493   .280
 2  3  1  15.296  2.742   .466
 2  3  2  14.885  2.535   .198
 2  4  1  12.891  3.349   .4
 2  4  2  12.213  2.093   .586
 3  1  1  10.623  4.721   .249
 3  1  2  11.693  5.06    0
 3  2  1  9.148   6.338   .1
 3  2  2  13.5    4.133   .05
 3  3  1  13.706  4.104   0
 3  3  2  11.369  4.489   .2
 3  4  1  11.21   5.104   .281
 3  4  2  10.439  2.606   .469
 ;

proc mixed data=corndamage;
 class timing rep befaft;
 model severe= timing befaft timing*befaft/ddfm=satterth;
 random rep(timing);
run;

proc mixed data=corndamage;
 class timing rep befaft;
 model minor= timing befaft timing*befaft/ddfm=satterth;
 random rep(timing);
 lsmeans timing befaft/diff;
run;

proc mixed data=corndamage;
 class timing rep befaft;
 model bcfm= timing befaft timing*befaft/ddfm=satterth;
 random rep(timing);
run;
```

Appendix D-4

```
        The SAS System      15:12 Thursday, October 17, 2002   1

                        The Mixed Procedure

                        Model Information

      Data Set                     WORK.CORNDAMAGE
      Dependent Variable           severe
      Covariance Structure         Variance Components
      Estimation Method            REML
      Residual Variance Method     Profile
      Fixed Effects SE Method      Model-Based
      Degrees of Freedom Method    Satterthwaite


                     Class Level Information

        Class     Levels    Values


        timing         3    1 2 3
        rep            4    1 2 3 4
        befaft         2    1 2


                           Dimensions

              Covariance Parameters              2
              Columns in X                      12
              Columns in Z                      12
              Subjects                           1
              Max Obs Per Subject               24
              Observations Used                 23
              Observations Not Used              1
              Total Observations                24


                        Iteration History

   Iteration    Evaluations    -2 Res Log Like       Criterion

           0              1        85.26826698
           1              2        83.31800412      0.01416105
           2              1        82.86565389      0.00307518
           3              1        82.77528638      0.00019165
           4              1        82.77013437      0.00000090
           5              1        82.77011103      0.00000000


                 Convergence criteria met.
```

SAS output - continued

```
The SAS System     15:12 Thursday, October 17, 2002   2

              The Mixed Procedure

             Covariance Parameter
                  Estimates

           Cov Parm         Estimate

           rep(timing)        4.8233
           Residual           1.8773


                Fit Statistics

     -2 Res Log Likelihood             82.8
     AIC (smaller is better)           86.8
     AICC (smaller is better)          87.6
     BIC (smaller is better)           87.7


          Type 3 Tests of Fixed Effects

                 Num      Den
Effect            DF       DF      F Value     Pr > F

timing             2      7.2         0.57     0.5885
befaft             1     6.48         0.00     0.9560
timing*befaft      2     6.46         0.26     0.7762
```

SAS output – continued

```
    The SAS System     15:12 Thursday, October 17, 2002   3

                  The Mixed Procedure

                   Model Information

Data Set                      WORK.CORNDAMAGE
Dependent Variable            minor
Covariance Structure          Variance Components
Estimation Method             REML
Residual Variance Method      Profile
Fixed Effects SE Method       Model-Based
Degrees of Freedom Method     Satterthwaite


               Class Level Information

 Class      Levels    Values

 timing          3    1 2 3
 rep             4    1 2 3 4
 befaft          2    1 2


                     Dimensions

         Covariance Parameters            2
         Columns in X                    12
         Columns in Z                    12
         Subjects                         1
         Max Obs Per Subject             24
         Observations Used               23
         Observations Not Used            1
         Total Observations              24


                  Iteration History

Iteration    Evaluations    -2 Res Log Like      Criterion

        0              1     86.64089576
        1              2     80.08214858      0.00000002
        2              1     80.08214798      0.00000000

             Convergence criteria met.
```

SAS output – continued

The SAS System 15:12 Thursday, October 17, 2002 4

The Mixed Procedure

Covariance Parameter Estimates

Cov Parm	Estimate
rep(timing)	4.4472
Residual	1.5082

Fit Statistics

-2 Res Log Likelihood	80.1
AIC (smaller is better)	84.1
AICC (smaller is better)	84.9
BIC (smaller is better)	85.1

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
timing	2	8.99	0.09	0.9143
befaft	1	8.21	6.00	0.0392
timing*befaft	2	8.2	0.96	0.4224

Least Squares Means

Effect	timing	befaft	Estimate	Standard Error	DF	t Value	Pr > |t|
timing	1		5.1950	1.1641	9.42	4.46	0.0014
timing	2		5.1324	1.1403	8.77	4.50	0.0016
timing	3		4.5694	1.1403	8.77	4.01	0.0032
befaft		1	5.6087	0.7216	12.1	7.77	<.0001
befaft		2	4.3224	0.7045	11.3	6.14	<.0001

Differences of Least Squares Means

Effect	timing	befaft	_timing	_befaft	Estimate	Standard Error	DF	t Value	Pr > |t|
timing	1		2		0.06259	1.6296	9.1	0.04	0.9702
timing	1		3		0.6256	1.6296	9.1	0.38	0.7099
timing	2		3		0.5630	1.6127	8.77	0.35	0.7352
befaft		1		2	1.2863	0.5251	8.21	2.45	0.0392

SAS output – continued

```
The SAS System     15:12 Thursday, October 17, 2002   5

                  The Mixed Procedure

                   Model Information

Data Set                        WORK.CORNDAMAGE
Dependent Variable              bcfm
Covariance Structure            Variance Components
Estimation Method               REML
Residual Variance Method        Profile
Fixed Effects SE Method         Model-Based
Degrees of Freedom Method       Satterthwaite

               Class Level Information

  Class     Levels    Values

  timing         3    1 2 3
  rep            4    1 2 3 4
  befaft         2    1 2


                      Dimensions

         Covariance Parameters            2
         Columns in X                    12
         Columns in Z                    12
         Subjects                         1
         Max Obs Per Subject             24
         Observations Used               23
         Observations Not Used            1
         Total Observations              24


                  Iteration History

Iteration    Evaluations    -2 Res Log Like       Criterion

        0              1        42.55375155
        1              3        28.78806307      0.43649505
        2              2        28.62317353      0.09456034
        3              1        28.47920409      0.00815660
        4              1        28.46721858      0.00008495
        5              1        28.46709979      0.00000001
        6              1        28.46709978      0.00000000

             Convergence criteria met.
```

SAS output - continued

```
The SAS System     15:12 Thursday, October 17, 2002   6

              The Mixed Procedure

             Covariance Parameter
                  Estimates

           Cov Parm         Estimate

           rep(timing)        0.3842
           Residual          0.04244

                Fit Statistics

     -2 Res Log Likelihood            28.5
     AIC (smaller is better)          32.5
     AICC (smaller is better)         33.3
     BIC (smaller is better)          33.4

         Type 3 Tests of Fixed Effects

                  Num     Den
Effect             DF      DF    F Value    Pr > F

timing              2    9.09       1.74    0.2292
befaft              1    8.17       0.99    0.3489
timing*befaft       2    8.16       0.26    0.7743
```

Appendix D-5

```
data soydamage;
 input timing rep befaft damage;
 datalines;
 1  1  1  16.75
 1  1  2  17.0
 1  2  1  19.75
 1  2  2  20.75
 1  3  1  21.75
 1  3  2  21.75
 1  4  1  20.75
 1  4  2  20.0
 2  1  1  19.25
 2  1  2  19.5
 2  2  1  16.75
 2  2  2  24.25
 2  3  1  23.5
 2  3  2  17.0
 2  4  1  25.0
 2  4  2  19.0
 3  1  1  22.25
 3  1  2  19.75
 3  2  1  15.75
 3  2  2  19.0
 3  3  1  15.75
 3  3  2  18.0
 3  4  1  18.75
 3  4  2  17.25
 ;

proc mixed data=soydamage;
 class timing befaft;
 model damage=timing befaft timing*befaft/ddfm=satterth;
 random rep(timing);
 lsmeans timing befaft;
run;
```

Appendix D-6

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The Mixed Procedure

Model Information

Data Set	WORK.SOYDAMAGE
Dependent Variable	damage
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Satterthwaite

Class Level Information

Class	Levels	Values
timing	3	1 2 3
befaft	2	1 2

Dimensions

Covariance Parameters	2
Columns in X	12
Columns in Z	3
Subjects	1
Max Obs Per Subject	24
Observations Used	22
Observations Not Used	2
Total Observations	24

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	80.38363296	
1	3	80.37111051	0.00000109
2	1	80.37108264	0.00000000

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Estimate
rep(timing)	0.05677
Residual	5.3994

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The Mixed Procedure

Fit Statistics

-2 Res Log Likelihood	80.4
AIC (smaller is better)	84.4
AICC (smaller is better)	85.3
BIC (smaller is better)	82.6

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
timing	2	1	1.26	0.5329
befaft	1	14.5	0.43	0.5215
timing*befaft	2	14.5	0.29	0.7547

SAS output – continued

Least Squares Means

Effect	timing	befaft	Estimate	Standard Error	DF	t Value	Pr > |t|
timing	1		19.5271	0.9980	1	19.57	0.0325
timing	2		19.8882	1.0272	1	19.36	0.0329
timing	3		17.6587	1.0896	1	16.21	0.0392
befaft		1	18.6957	0.8136	1.04	22.98	0.0250
befaft		2	19.3536	0.7477	1	25.88	0.0246